In the name of Allah, the beneficent, the merciful

مشخصات انسان سبکبال ، چابک , پویا، بصیر وصاحب عزم برای ایجاد توسعه پایدار(از طریق حرکت در اعماق وجود)

Characteristics of human of passerine, agile, dynamic, insight and resolute for creating of the sustainable development (by the way of movement in the depths of existence)

بر اساس قوانین نیوتن وقواعد دانش مفید

Based on newton's laws and useful knowledge's rules

آنچه تا کنون از اندیشه ودست آوردهای دانشمندان کشف وضبط وبه علم وفناوری تبدیل شده است با آنچه باید فهمیده وبکار گرفته شود ، اندکی بیش نیست ، برای پیشرفت های علمی وفناوری بر اساس درک ذهنی وقلبی ازمکاشفه دانشمندان حقیقی ، بستگی تام به قوه کنکاش فکری وجاذبه های قلبی انسان های فهیم مربوط میشود که امری نسبی ، اعتباری بوده وکمتر به جریان های حقیقی ارتباط پیدا کرده است و با درک بیشتراز جریان حقیقی انطباق وارزیابی های حقیقت یاب آن ، از خمیر مایه های ذهنی ومنویات قلبی متفکران یکتا پرست ، بهره برداری میشود.

What ever thought and discovering of scientists have changed to T&S, by what should be understood and done, not just over, for progressing about S&T based on the mental perception and understanding heart from true Scientists, s revelation, related to find dependent on the power of thought and heartfelt attraction man of understanding that is relative ordered and reliability and has linked to truth currents lesser and by Understand than the actual conformity assessment operation is from the mental yeast and heart intentions monotheistic thinkers.

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برای اینکه لَختی وفَربِگی را ازبین ببریم باید جاذبه های غیر ضرور را به صفر برسانیم

In order to eliminate inertia and fatten body should be to zero the unnecessary attractive forces

بازوی گشتاور همان مردم وبخش خصوصی بوده ونیرو نیوتنی هم تراز منابع کشور ونقطه اتکا قوا ورهبری نظام است

The torque arm is stress of people and private sector, Newton force alignment of resources and force leadership is based on point system

برای رسیدن به توسعه پایدار درهر کشوری ، نباید هیچ کسی ،عاملی ، مولفه ای از کوچک تا بزرگ رها شده باشند وباید تمامی موجودیت های یک کشور براساس جریان انطباقی وقاعده تکلیف وحقوق بکار گرفته شود، در غیر این صورت نیرویهای رها شده به بازدارنده ها وموانع ایجاد توسعه تبدیل میشوند ، این موضوع مهمی است که دراین تحلیل اثبات میشود.

For achieving of sustainable development in any country, mustn't be abandoned at all, like: anyone, any factor, any component from small to large and should all entities in a country be busy based on conformity current and rule of duty-right, otherwise , released forces will changed to disincentives and obstacles to development , it is important subject that this analysis proved.

سه چیز در موضوع توسعه پایدار مهم است :

1- سرعت وحداقل سازی زمان رسیدن به توسعه (سرعت از این نظر حائز اهمیت است که موجد شتاب است وافزایش شتاب ، قدرت جاذبه وکشش های غیر ضرور را کاهش داده وسنگینی ولختی را (اینرسی) به حداقل میرساند واین اقدام فقط به فقط توسط مردم وفراوانی های (چگالی) درون آنان ممکن است
2- فعال کردن همه منابع کشور (منظورم از همه منابع ، فقط معادن ، دریاها ، زمین ها وامثال اینها نیست ، منابع نامحسوس ،بلکه نهان وآنچه در پشت پرده برنامه های دولت است از منابع فیزیکی کشور بیشتر است ودستیابی به آنها از فیزیکی آسان تر، مثل ابر پروژه ها)
3- ایجاد حداکثر ارزش افزوده (ارزش افزوده را در محصولات نهائی با کارآمدی فناوری وقابلیت مصرف در عمق تکنولوژی دنبال میکنیم)

Three things are important in Sustainable Development:

1. Quickness of apprehension and to minimize time to will be development (Speed is important in this regard that causing of acceleration and

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Increasing acceleration, and reduce the strength of gravity and the unnecessary elasticities ,and will get to minimize the heavy and inertia and this action can only be the only by people and density may be within their).

2. Activating of all country's resources (I mean, from all sources , These arms will not land, mines , seas and like these , but intangible resources and what is behind of state's plans and those are more that tangible resources and physical access to them easier, like: mega projects)
3. Creating maximum value- added(we should follow the all value-added in final productions through efficient use of technology, in-depth technology capabilities)

تعادل های وزنی وقبول تیپولوژی حقیقی آن در امر تکوینی الگوی توسعه پایدار:

1. ما بدنبال آن نیستیم که موضوع بی وزنی در میکانیزم نیوتنی ، قاعده ای برای میکانیزم های تصمیم گیری سیاسی ومدیریتی است ، یعنی هر گونه تصمیمی را خالی از وزن بدانیم ،نه ابداً، ولی زدودن سنگینی غیر قابل تحمل که مانع توسعه شود ، یک ضرورت است
2. باید وزن وسنگینی هر کفه ترازوی دولتی وخصوصی ، برای تجمیع قدرت تصمیم گیری در امر توسعه پایدار متناسب شود
3. موضوع پر اهمیت فوق مارا به تعیین مقیاساتی برای قدرت تصمیم گیری هدایت میکند که با ارزیابی انطباق از معیاری منبعث از قواعد دانش مفید نیاز است دراین مورد ما بدنبال احکامی هستیم که مصداق داشته باشند .
4. پرواضح است که اگر جاذبه زمین صفر شود همه اشیاء روی زمین بی وزن شده وزمین متلاشی میشود ومرکز تقارن برای جذب اشیاء وجود ندارد

Balancing of metrical weight and accepting of true typology in conceiving a model of sustainable development:

1. We are not looking for that the theme of weightlessness in Newtonian mechanics, it is a such mechanics for undermine the decision-making in political and managerial affairs , this means that any decision without knowing weight not at all, but it is necessary , eliminating the intolerable burden that is hindering development .
2. Must be proporting of balance the heavy weight of republic and private, for undermining the decision-making on sustainable development.
3. The above important subject guides us to determine many scales for power of decision-making that it necessary to conformity assessment of criterion

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relates useful knowledge, s rules; hereupon we're following the rules applicable.

4. It is obvious that if zero gravity (G-0), all objects are weightless on Earth and Earth will decays and there is no symmetry center to attract objects (سوره ۸۱ التکویر).

چگونگی ایجاد فشار آزاد ونحوه مهار آن:

1. فشار آزاد خطرناک است ، بخصوص که القائی باشد ، در حقیقت فشار آزاد تصمیم گیری عقلائی را عقیم کرده وگاهی خنثی ساخته وباعث فروپاشی میشود .
2. سکوهای عمل برای توسعه پایدار باید با اوزان متناسب تراز شوند واز مرکز تقارن تبعیت کنند.
3. موضوع تفکیک تکالیف دولتی وخصوصی نباید در اختیار فشار آزاد قرارگیرد ابداً، برای اینکه طرف دیگر را بی وزن میکند .
4. سنگین شدن یک قسمت از کل سیستم ، بطور طبیعی از ثقلیت سایر قسمت های سیستم می کاهد وباعث بی وزنی یا کاهش وزن آن قسمتها میشود

How to create a free stress and how to halter it:

1. Free stress is dangerous, which is particularly inducting it, in truth, free stress will bring to naught the rational decision making and sometimes causing the collapse is foiled.
2. Operating platforms should be balance with appropriate weights and to abide by their symmetry center.
3. Separating public and private assignments should be made available free stress at all, to the other side out of the weight.
4. Becoming heavy one part of the whole system, decreases of other parts of whole system and weightlessness or weight loss that is caused to that sections

ما در دنیائی به سر می بریم که مسئولین آن واقف باین حقایق نیستند(به مقاله حقیقتِ حقیقت من مراجعه کنید):

1. فکر نکنید که اگر قسمتی از سیستم شما بی وزن شد ، از خاصیت وفعلیت باز می ایستد ، خیر ؛ بلکه باعث میشود سرعت زیادی گرفته وبطور طبیعی سیستم های تحت عمل شما را عقیم کند ودر این شرایط ،سیستم شما بطور طبیعی وشایسته کار نمی کند.
2. مشکل کلی جهان در غفلت هایی از این قرار هستند، یعنی فقری که اینک در جهان مستولی شده است کمر هر استیلاء را میشکند وظلمی که که صاحبان قدرت روا داشتند موجب بدهی های

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سنگین ، افزایش تسهیلات هسته ای ، ونظیر اینها شده است که دیگر قابل مهار نیست ، این طبیعت سیستم هااست .

3. ما خیال می کنیم که سازمانهائی نظیر حقوق بشر ، سازمان امنیت ، آژانس هسته ای وغیر اینها ، چون متکی به استکبار جهانی هستند ، نمی توانند به اقدامات سالم مبادرت کنند ولی از نظر من ، این ها از مدار سیستم فرو افتاده اند(این موضوعات را من دررساله هوشمندی جهان نوشته ام)
4. پس چگونه می توانیم از بی وزنی اجتناب کنیم :

4.1. باید به هر زیر سیستم ملی ویا بین المللی ، بطور متناسب قدرت عمل بدهیم تا بتواند از قوا وفرصت های دراختیار خود ، به وظائف خود عمل کرده ومتقابلاً دارای حقوق باشد (رساله حقوق متقابل امام سجاد علیه السلام)

4.2. خط سیر کسی را در توسعه هم آهنگ جهانی وملی مسدود نکنیم

4.3. بال های پروازکسی را ناقص نکنیم ویا بال او را از بدنش جدا نکنیم وسیستم اورا به عنوان قسمتی از سیستم جهانی خراب نکنیم.

4.4. در همکاری با افراد در تکالیف جهانی یا ملی اجتناب نکنیم (مثل رفع آلودگی محیط زیست)

4.5. موضوع مهم اینست که انسان پویا از طریق قاعده " تکلیف – حقوق " شناخته میشود

4.6. کل سیستم را می توان به کل تکلیف تعبیر کرد که این کلیت مبتنی بر علیت تراکمی است و از تکالیف- حقوق تبیعت میکند و آنهائیکه خودرا زرنگ میدانند در آخر صف هستند.

4.7. باید بدانیم کلیه نیروهای ملی وبین المللی برداری هستند(نه اسکالر) وخصیصه برداری دارند ودارای جهت ، هدف ، مقدار قدرت ، سرعت ، قدرت خنثی سازی ، افزودگی ، کاهش کنندگی واز این قبیل هستند.

We living in a world that the authorities are not aware of the facts hereto (refer to my article as truth of truth):

1. Do not think that if part of your system without weight, Property and fly it stops, never, but it makes too much speed and your systems will get inactivate naturally and under this condition , Your system does not work normally and merit.
2. The general problem of the world are the neglect of these matters , namely that poverty is prevailing now in the world , will breakdown waist any ascendency and oppression that those in power have done it caused became heavy debts , increase nuclear facilities and etc. that could not restrain, this is the nature of the systems.

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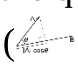
3. We think that organizations such as Human Rights, Security organization, non-nuclear agency and such these, because they are dependent on global arrogance, they cannot make well actions, but in my opinion, these systems have fallen from orbit (These things I have written in the treatise of global smart).
4. So how can we avoid the weightlessness:
   - 4.1. We should give to any national or international subsystem a weight proportional power operation till it can of promise and opportunities at their disposal Fulfill obligations and rights reciprocally (the epistle of reciprocal right from imam Sajida peace upon him).
   - 4.2. The direction of its way (trajectory) will not blocked it in national and international harmonic development.
   - 4.3. Not defective its wings or not separate it's from his wings and not distorted its Systems as part of the global system.
   - 4.4. We no avoid in partnership with him in domestic or global assignments (Such as the elimination of environmental pollution).
   - 4.5. The important thing is that dynamic human is known through the principle of "duty - law".
   - 4.6. The entire system can be explain to equal on entire duties that The whole is based on cumulative- causity , and it abide by the rule of "duty - law" and those who consider themselves wise are in the queue.
   - 4.7. We should know all national and international forces are vector ()not scalar and its spec is like vector shape , and having mix order, purpose, amount of power, speed and etc.

قضایای مدیریت کوانتومی ودر رابطه با قوانین مکانیک نیوتن

1. فرضیه های مدیریتی گذشته ، عمرش تمام شده است .
2. ما میبایست با استفاده از موضوعات علمی وبا رویکرد غیر مادی (مانند موضوعات مفصّل از دانش مفید از این نویسنده) به مهارت های جدیدی در مدیریت دست بیابیم
3. علیت تراکمی که یادگار گونار میردال است ، نشان داد که بایک علت نمی توان به یک ویا چند معلول رسید ، لذا در علل موجده بر معلول ویا چند معلول متراکم شده ، علل زیادی از مادی ومعنوی دخالت دارند

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4. تفکر مادی ومکانیکی دارای عرصه محدودی است و ذهن قادر به کشف وشهود عرصه بینهایت وروشنگر آن نیست ، وانسان خالی از این نیروی جاذبه ، قادر نیست جرم های موجود در حیات بشررا برای سعادت بشر به اوزان مناسب برای توسعه پایدار تبدیل کند
5. بسیاری از فرضیه های مدیریتی رایج از ماده فهم اخذ نشده است بلکه آغشته با وهم است

The circumstances of Quantum management and relets to Newton's mechanic laws (1):

1. The last managerial hypotheses finished their life.
2. We must achieve to new skills into management by using of scientific subjects and non- materials approach (like: the details of usefulness knowledge from this writer).
3. The accumulative causity that was commemoration from Gunnar Myrdal, it showed that couldn't to one or many results by one cause, so there is much interference for convening of one effect or many effects.
4. The material and mechanical thinking is limited, and mind cannot to discovery and witnessing of extreme existence at all, and human those who whit empty these attractive forces in itself not able change these life's mass into necessary happiness for human and weights for sustainable development.
5. Many of present managerial hypotheses were not take from understanding relates materials, but those are groundless opinions or fancies.
6. موضوع مدیریت ، مسئولیت پذیری وسایر شاخصه های فی ذات انسان ، مستلزم شناخت مدیریت کوانتومی (ذره ای) از نوع معنوی است
7. آنقدر که قدرت دید ، مشاهده گری وتوانائی مدیریت درشناخت شهودی است که از شناخت پوپری حاصل نمی شود .
8. ما باید در اقیانوس درون خویش سیر وسفر کنیم تا از قدرت جهانی آگاه شویم (مراد امام علی(ع) از این عبارت چیست: «شما فکر می‌کنید یک موجود کوچک هستید، در حالی‌که کل جهان در درونتان نهفته است»؟www.islamquest.net " خانه ، گنجینه پاسخ‌ها و حدیث")
9. پیام کوانتم یعنی انسان سازی برا ی پویائی ، آگاه سازی ، عزم وجزم وچابکی واینکه می گوید " ما سَمیعیم ، بَصیریم وهُشیم ، با شما نامحرمان ، ما خامُشیم " .
10. ادراک کوانتومی فقط ذهنی نیست ، بلکه همراه با درک قلبی است (آیه 78 سوره نحل" وَجَعَلَ لَكُمْ الْسَّمْعَ وَالابصَارَ وَالأَفْئِدَهَ لَعَلَّكُم تَّشكُرُونَ"درقرآن) که الهامات اشراقی را ممکن میسازد .

The circumstances of Quantum management and relets to Newton's mechanic laws (2):

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6. The subject of management, it means responsibility and other humam,s specs in itself , is necessities to have known quantum management of spiritual kind so that should be suitable for human .
7. So that visibility, perceivably and managerial ability are in intuitive understanding, that does not come from popper's knowing.
8. We should go on journeys into our inner's ocean till can aware from universe power" you think that you are a small existent! While the whole world lies in yourself (www.islamquest.net" خانه ، گنجینه پاسخها و "حدیث – Ali peace upon him).
9. The message of quantum it means making human for dynamic, awareness, agility , insight, and resolute for creating of the sustainable development and it says:" we can hear, insight, vigilant, whit you strangers, we are silent"
10. Quantum is not only subjective perception, but along whit Understanding heart(in Quran" and Allah has extracted you from the wombs of your mothers not knowing a thing, and He made for you hearing and vision and intellect that perhaps you would be grateful. " Sura Bee verse 78, from Quran) That enables intuitive inspiration,
11. ما می خواهیم از این درک وبصیرت در طراحی توسعه پایدار با رویکرد وپارادایمی متمایز استفاده کنیم .
12. آنچه در فوق گفته شد ، خمیر مایه وطبیعت کار دانشمند در خلوت های اوست وحاصل آن تغییر دادن دنیای بشریت در روی کره زمین از طریق کشف راز های این جهان هستی است(پارادایمیک است)
13. بحث نیوتن در مورد نیروی گرانشی وجاذب بصورت خرُد(Micro- G)نگاه متمایزی در دید گاه نیوتنی است که مربوط به ذرات ومحیط در برگرفته آنست که به عقیده من مورد غفلت در مدیریت قرارگرفته است یعنی بین " Microgravity "و " Weightlessness "سازگاری بنیادینی را درک میکنیم که خلاصه ای از آن در ابتدای این بحث آمده است ونشان میدهد در چنین حالتی (Zero-g)ما درمدیریت به نیروهای جاذبه (g-Forces) میرسیم وآن حالتی است که به مفهوم گشندگی" Tidal forces" میرسیم (به تئوری های نیوتن در انتهای این مقاله توجه کنید) که می خواهیم درمورد این اثر در امر توسعه بحث کنیم .
14. معنی ومفهوم " Tidal"بمعنی گشندگی (مثل جریان جزر ومد دریا) همان اشاره ای بود که قبلاً بیان شد ، خیزش های گشنده(Attractive rise or jump) نظیر خیزش موشک های با کلاهک هسته ای است ، بسیاری از مردم ساده دل ، موج ها را توفنده تعبیر میکنند ، در حالیکه ازمبداء امواج مکانیک ذره ای سرچشمه میگیرد نه از میکانیک گشتاوری نیوتنی ، این موضوع در مکانیک خاک بیشتر مصرف دارد وخاک شناسی در مرداب ها (یعنی جائی که

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امکان خیزش را در اذهان منتفی جلوه میدهد)، در حال رها شدن همین مرداب وخشک شدن آنها ، به توفان شن وریزه گردها وتخریب های وحشتناک منجر میشود .

15.آنچه در قلب وذهن نیوتن یکتا پرست ، جریان داشت این بود که جاذبه بر جرم نیرو ایجاد میکند وشامل اجسام بدون جرم نمی شود ، ولی درکی که اواز ذرات ویا اجسام بی وزن داشته است ، رهائی آنها در عرصه های خود مختار وخود انتخاب است ، مثل اینکه ذرات خاک که به زیرتکالیف کِشت وزرع قرار نمیگیرد ، تغییر ماهیت میدهد وکارشناس خیال میکند ، این ذرات بی خاصیت شده اند ، نه دارای خاصیت دیگری شده اند که در جریان توسعه درک شده وبکار گرفته میشود ودر عرصه های بدون علم وفناوری این گونه خاصیت های شناخته نشده ، ولی همین خاصیت ها در زمان ومکان مقتضی ، ماموریت خیزش گشنده ویا در درک ساده ، خاصیت خیزش های تخریبی دارد .

The circumstances of Quantum management and relets to Newton's mechanic laws (3) :

11. We want to use this understanding and insight in the design of sustainable development by approach and distinctive paradigm.
12. What was said above, scientists, s yeast, the nature the privacy of him, and consequently he could change the world of humanity on the way of discovery this universe's mysteries as a paradigm.
13. subject matter from Newton relates gravimeter and absorbers crushed" Micro-g", Newton's distinctive look is in his view, which surrounds the particles and its environment that I believe that have been neglect in managerial affairs , it means , we understand the fundamental compatibility between "Microgravity "and "Weightlessness "that its abstract at the beginning of this discussion has come,in this case shows "Zero-g " so , we will reached to management of the forces of gravity" g-forces "it is how a position when we will reached to concept of "Tidal forces "(pay attention to Newton's theories at last of this article),we want to discuss about this matter in order to sustainable development .

14. Conceptual meaning of "tidal" accretive meaning , (Like the sea ebb-tide) as was mentioned previously stated, attractive rise or jump such as the rise of missiles with nuclear warheads, many people are simple-hearted , they interpret of the waves are crashing, while stems from base of quantum's waves , this subject have more consumption in soil mechanics and sociology of the swamps(where the possibility of uprisingin the minds seem canceled) , at the

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release of the marsh and dry it leads to sandstorm , petite tourists and dreadful destruction.

15. Whatever at the heart and mind of monotheist Newton has curetted , it was then that gravity is the force exerted to mass and it does not include mass but understanding when he was weightlessness particles or objects, their liberation of self-determined and self-selection is, it seems that the soil particles under duty not be cultivated, change the nature of the essence and relates expert thinks that these particles have been useless , not have another property that in During the development of perceived and take it busy and in scope without S&T, such these aren't known their particular for suitable using , but this features in due time and place , having mission for destruct rising dangerously.

16. من موفق بودم که سرگذشت بیشتر دانشمندان وفلاسفه را مطالعه کنم ، بین درک ذهنی وقلبی نزد اهل خِرَد در هنگام بیان اتو بیوگرافی وبیان فرضیه ، تفاوت چندانی نمی بینی ، او در سیر وسلوک در درون خویش (مونولوگ)که بیشتر ذره بینی (Lenticular or microscopically)است به اعماق ذره ای توجه دارد ، پس نباید تنها به بیان فرضیه او توجه کرد، بلکه به درک ذره ای او باید پرداخت .دانشمند تغییرهر ماهیت را در زمان خود احساس نمی کند ، هر قدر که فرضیه های یک دانشمند سخت فهم تراست استفاده از آنها ، دیر فهم تر خواهد بود ویا عده ای بطور ناقص از فرضیه های او درعلم وفناوری استفاده میکنند .

17. I was able to success that studied story of scientists and philosophers, between mental understand and heart perception with wisdom when the state of auto biography and his theories, you don,t see much difference, he filled in his inner (monologue) that is more Lenticular or microscopically , he pay attention to depths of iota ,then you should not only be considered hypothesis states , as much as hard to understand of a scientists,s theories , use them later be more understanding or somebody use from his hypothesis in S&T defectively.

18. دانشمندان حقیقت طلب ویکتا پرست فرق اساسی با کسانی دارند که با اندیشه والقائات خود جهان را به تباهی کشانده وتلاش دانشمندان ارزشمند را خنثی نموده ویا موجب شدند که عده ای از دنیا پرستان تحت عنوان علم وفناوری ، با استفاده از دست آوردهای دانشمندان خیر خواه ، زمینه ها ووسائلی ساختند که محیط زیست ، عدالت توزیعی ، تکلیف وحقوق وانسانیت را به نابودی بکشانند، یکی از این دانشمندان یکتاپرست آلبرت انیشتن بود که در کودکی نظیر نیوتن از نظر جسمی ضعیف بود ولی با نگاهی به کائنات ، هیچ گاه تن به سرگرمی های بیهوده نداد وتمام عمررا برای سعادت بشریت تلاش کرد ومانند نیوتن از مردم ، از خانواده خود وهمکارانشان آزار وشکنجه دید ، او نیز از نظریه ثقل وجاذبه عمومی به نظام هسته ای وذرات وجود جهانی

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پی برد وفرمول او در فیزیک معادله جرم-انرژی($E=mc^2$) مفهومی فرمول‌بندی شده توسط آلبرت انیشتن بود ،معادله نیوتن هم بیانگر اصل هم‌ارزی جرم و انرژی است که از فرمول (Weight = mass × −g-force)منبعث میشوداز طریق نیوتن کشف وآشکار گردید ، ولی همانطور که از قوانین نیوتن موشک برای نابودی بشر ساختند ، از معادله انیشتن کلاهک هسته ای بر سر این موشک های کشتار جمعی قراردادند وریکهایمر با دزدیدن این علم از انیشتن به آمریکا رفت وبا شیطان بزرگ دو بمب بزرگ وکوچک بر سرژاپنی ها افکند ومیلیون هاانسان را نابود کرده وهنوز زخمی های اتمی آنها التیام نیافته است ، اگر ریکهایمر در سه ماه بعد دقمرگ شد ، ولی غصه انیشتن هیچگاه دراین جنایت فراموش نشد و گفت :" کاش من یک کفاش بودم"https://books.google.com/books?isbn=1317698959

19. Scientists seeking true worshipers and monotheist have basic different with those who by its thoughts and selves inductions world wrecking and have neutralized struggle of invaluable scientists or caused the number of worldliness lead to the destruction of humanity as under the Science and technology , these men by the achievements of scientists using well-wisher, have built areas many means for depredating environment, distributive justice, what about the rights to humane , in the meantime, Albert Einstein was one of the scientists Unitarian that he has a body Physically weak as a child, like Newton but looking for at the universe, didn’t itself in vain to hobbism never, and all lifelong tried to making for the good of humanity , and like Newton, saw Persecution of his family and colleagues ,He is also the theory of gravity and gravitational general, found the global system of nuclear particles , and his mass energy equation ($E=mc^2$) a concept was formulated by Albert Einstein, Newton's equation expresses the principle of equivalence of mass and energy that (weight = mass × -g-force)emanates formula , but as from Newton's laws made missiles to destroy human, from Einstein’s law Nuclear warhead over missiles of mass killing , and Ricky Haimer (American) by stealing the science of Einstein went to America and with the Great Satan , he can make andTwo big and small bombs are dropped on Japanese’s people and destroyed Add millions human, and still not recovered their atomic vounds ,if Ricky Haimer three months later was died from marasmus, but Einstein never forget this crime were grieved and said : “I wish I was a shoemaker”.

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20. ما باین موضوعات توجه لازم را داریم چون حقیقت است وراهنمای دولت ومردم و اجزای مختلف ومتنوع آنرا در دانش مفید گرد آوردیم ،علم مدیریت جدا ازاین اندیشه های ناب نیست ودر محاصره تفکر صِرفِ غربی نیست ، ومن بصراحت می گویم که اگر کسی در مسند مدیریت از چنین فهم عمیق برخوردارنباشد ازاحکامی که میتواند اورا در بحران های پیچیده یاری کند ، محروم خواهد بود وآخر الامر راهی به جائی نمیبرد ، او مدیر لایقی برای رتق وفتق اموری که بوی ارجاع شده است ، نیست واین موضوع درد ورنج اصلی دنیای امروز ماست ، مدیریت خمیرمایه ای از این ذره شناسی است ونه فقط برای حل بحران های سنگین با اینرسی بزرگ ، بلکه این موضوع نیازمند جزئی سازی هر امر بحرانی پیچیده از طریق شکست بحران های پیچیده برای پیدا کردن کلید های حل مسائل است ، فراموش نکنید که قاعده مورد نظر ما در شکست بحران های بزرگ ، تنها امورمادی آن نیست وباید از فاکتور معنوی بر خوردار باشد.

21. For these subjects , we have pay attention necessarily, because those are the truth and Giddiness the people and governance and we brought together them of different components into useful knowledge, management is not a part of these pure knowledges and it doesn't in the besieged western spent thinking at all, and i explicitly say that if anyone not be successful such a deep understanding on management's seat will be deprived from commands for remedying the crisis and state's governors last way to nowhere ,he is not competent manager for handling affairs that referred to him and this subject the main suffering is our pain today, management is yeast of this particlelogy , not just for salving heavy crisis, but it is necessity for destabilizing of any big crisis(or mega project) as breakdown of critical components into enforceable for finding keys to solutions and don,t forget that rule our requisite in breakdown of big crisis , not only material factors and Should enjoy the spiritual factor is.

22. من مایل هستم هشدار بدهم که مدیریت باید توجه خود را به محیط های غیر یک نواخت " non-uniform or non- routine " بیشتر معطوف کند ، ساده اندیشی مدیران باعث شده که به یک نواختی تکالیف بیشتر عادت کنند واز فشار ناشی از تغییر شکل گیری " deformation " غافل شوند لذا باید بدانند که فشارهای ناشی از غفلت های ذره های ناآشکار ، موجبات هم تخریب وهم جذب سایر اشیاء غیر متعارف دارد ، واین مشکل اصلی غرب در مطالعات آینده نگری وتجزیه وتحلیل های امور پنهان درجریان است (مراجعه به یکصد مشکل امریکا از این نویسنده) ، آینده نگری با رمل واسطرلاب وبازی های ریاضی قابل تشخیص نیست وما را بیاد مرتاض ها وکیمیاگرهای دوران اساطیر می اندازد (به مقالات من تحت

عنوان سوغات غرب مراجعه نمائید) ما درآینده نگر ی نیازمند ، قواعد دانش مفید ، جزئی سازی امر پیچیده برای پیدا کردن راه حل های کوچکتر وتوجه بمقدرات الهی هستیم .

23. I would warn that management should turn draw to non-uniform or non-routine more , Simple-minded managers make caused that more be accustomed to the humdrum tasks and the burden of changing the deformation attend, they should know that Pressures caused by the negligence of hidden Particles Caused the destruction of both the absorption of other unconventional objects and this is essential west's problems in future studies and analyzing of covert Affairs during the hidden currents (refer to America a hundred problems from this author), futurology not detectable with geomancy and the astrolabe and mathematical games ,we have remembered the ascetic and old age of Mythology casts transmutation of metals (refer to my articles as west's Souvenirs) , we need to know defining forecasts the rule of useful knowledges, making of partialized of the complex matter for finding small solutions and according divine's decrees.

24.پدیده های خُرد جاذبه " phenomenona of micro gravity " در هنگام عمل ، سکوساز بوده وبسیار قوی تر ازپدیده های کلان جاذبه " PoHG " اثر طولانی میگذارند ، شاید مثال سیه چاله " Black hole " دراین مورد بی مناسب نباشد(یعنی ما آنقدراز ذرات اتم روی زمین استفاده ها کردیم که از بزرگ گوئی های سیه چاله ، هیچ نصیبی نداشتیم !)

25. phenomenon of micro gravity, when it is in action and was the platform very strong more than "PoHG- phenomenona of macro gravity "have long effect , maybe example Black hole without appropriate in this case (that is enough what we useof atomic particles on Earth that we had no inheritance from Great speeches of Black hole!).

26.چارچوب هائی که از مرجع اینرسی" Inertial reference frameworks " منبعث میشوند وهدایت های لختی را بطور خودکار اِعمال میکنند ، این قاب ها ویا چارچوب ها را آشکار نمیکنند ، دراین مورد برای بینندگان از زمره اَشیاء نامحسوس هستند ولی داری سیستم های خود ساخته اجتماعی بوده ، واین گونه هدایت های لختی را در موقعیت مناسب ومقتضی بکار میگیرند (به موضوعاتی نظیر فقر جهانی ،زور گوئی های امریکا ، مصائب سرمایه داری وغیره توجه شود ودراین مورد به مقالات این نویسنده در سایت علم مفید مراجعه شود) ، جالب است که این هدایت های غیبی ، همانقدر برای اردوگاه شرور خطرناک است برای اردوگاه خیر اندیش راهبردهای جدیدی را نشان میدهد(مکر دشمنان خدا ضعیف است ، قرآن آیهٔ 76 سورهٔ نساء، انّ کید الشیطان ضعیفاً) ، بعضی سفیران ، رایزن های فرهنگی ،بازرگانی

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وغیره در اکثر موارد، فاقد این بصیرت های عمیق هستند ولذا در مذاکرات دارای برگ برنده نیستند(نظیر طرح جهانی حلال د رایران).

27. The frameworks those it is derived from inertial reference frameworks and it automatically exercised inertial guidance, this frameworks will not revealed, in this regarding to for viewers are intangible objects, but they have self-made social systems and such this inertial guidance used in the proper position when be advisable (refer to many from me about world's poverty, America's compulsion, disaster of capitalism and etc.) ,it is interesting that this hidden guidance, as for the wicked camp will be dangerous, for benevolent camp shows new strategies(the trick of enemies of God's plan is weak- Quran- woman surah- verse 76) many ambassadors , cultural counselors , commercial and etc. in most cases. Not having much these depth insights, therefore they have not the win card in the negotiations (Such as the global plan's Hallal initiative of Iranian).

28.مایه تعجب است که در بعضی از کتب علمی آمده ، کسانی که به مکانیک ذره ای آشنا شده اند از مکانیک نیوتنی خدا حافظی کرده اند ، هر دو اینها از حقایق دور هستند برای اینکه مواد حقیقی همه حقایق ، به یک مرکز تقارن متصل شده اند که فهم این مهم ، مربوط به کسانی است که در دانش مفید وحقایق درون آن با تقوای لازم سیر وسلوکی محققانه داشته باشند وگرنه دچار نیروهای حاصل از خیزش های کنار زننده " Withdraw laid-up " قرار میگیرنند، تمام علم یکی بیشتر نیست ، ما به شعبات آن توجه داریم وبخصوص به قسمت که جنبه پول سازی فصلی دارد وکاری به آینده آن نداریم واینکه چرا فرضیه ها وکار کرد های علم وفناوری تغییر میکند ، دیر فهم میشود.

29. It is surprising that have come in many scientific books ,those who Have been met to quantum mechanics , they have said goodbye from classical mechanics(Newton), both of these truths are far away, to be true all material facts, connected to a center of symmetry that is important to understand relates of those who has travelling and behaviour in use fullness knowledges and the truths that pious necessary and otherwise, they will settle experiencing forces of the withdraw laid-up , all science is one, we are concerned their branches and particularly in the aspects of seasonal money-making and why later understood of changing of hypothesis and their operations.

30.آن خُرده کارکرد های مفید هنگامی مفید خواهند بود که ازیک کل حقیقی سرچشمه بگیرند ، این عمق نگری حتی به شما می فهماند که فراوانی آماری (چگالی) نشان از حقیقی بودن یک

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قسمت از کل نیست ، مگر اینکه با قواعد دانش مفید در سطوح شکست کل به جزء آشکار شود وبررسی جزئی از جزء دیگر که نتیجه تحقیقات حسی- ابطالی است ، بشر را به گمراهی برده است وعمدتاً القائی است که با تضارب افکار کشف وتولید میشود ، این موضوع اندیشمند میان رشته ای مجاب میکند که در یک شکست از قیاس به اجزاء تام ، از لحاظ تکلیف – حقوق ،هیچ ذی نفعی را از قلم نیاندازند ، عدم توجه به ذینفع ، بزرگترین تحریم نامحسوس بوده وبر حسب قاعده جری- انطباق ، لاضررولاضرار به تعادل درونی این تحریم ها پرداخته وسایر قسمت های تصرف شده را در اختیار حوادث مقدر مثل زلزله ، سونامی ، خشک سالی ونظیر اینها قرارخواهد داد، دراین مورد ذره ای تردید نداشته باشید .

31. Those fragmental useful earning when will be useful to get a good result from one of the true source , this depth of the review, even you know that statistical frequency (Density) being a part of the whole show is not truly, unless by rules of useful knowledge be revealed into breakdown levels of the component, and survey any part of the other another that is the result of research sensory- false,s rule , taking of human to error and that is mainly inductively , in the way of exchange ideas for discovering and production , this subject get assures interdisciplinary scientist the in a breakdown of components detailized of any total, according to the task – rights, no beneficiary who having interest to not put pen, due to lack of interest(beneficiary) is the biggest and intangible sanctions and in terms of rule current- conformity , harm to themselves nor to others without pay attention tothe sanctions dealt to inner balance and captured other benefit ,then will fix these currents like predestined events like earthquakes , tsunami, drought and etc. do not hesitate in these cases molecularly .

32. اقداماتی در طراحی ها ، نظیر شبیه سازی ، تنظیم الگوریتم ها ، مدل سازی وبسیاری ازمصورسازی ها (گرافیک نمائی ها) جستجوئی است از ظواهر پدیده ها ونه از درون حقیقت ها ، ویک گرافیست درون گرا که در این اقیانوس سیر وسفر میکند وتحت جاذبه های مواد دنیوی قرار نمیگیرد ، مانند یک شخص متقی است که تحت اینرسی ولختی این دنیا قرار نمی گیرد وقدرت طی الارض پیدا میکند واین آثار از هنرمندان درون نگر ، شاعران دارای الهامات الهی ، نقاشان ذره بین وسایر مصورسازها ی بنیادین بوده، وآنها در عرصه جهانی نامور کرده وآثار آنان هیچگاه کهنه نمیشود.

33. The initial steps in any design ,like: simulation, set of algorithms, modeling and Many are illustrated graphic , indeed , it is seeking of appearances phenomena and not inner truths and an introspective artist who is traveling in this ocean and is not under material attractions , he is a

pious person who does not fall under the inertia of the world and finds to during power on earth and this effects from introspective singer, divinely inspired poets, painters magnifying glass and other inner graphics those who was famous in the world and their effects never be old in the world.

34.دلسوزی مرا جدی بگیرید ، آنهنگام که یک انیرسی (لختی) سیطره خودرا بر سایر قالب ها (چارچوب ها) سیتم های اجتماعی ومحرک های توسعه تحمیل کند ، خود به نیروی ای خطرناک وتخریب کننده تبدیل میشود ، این پدیده بنام سهوی یا غیر عمدی (Unintentional) است ، یعنی اشتباه فهمیدن در اموری است که دراطراف ما ظاهر میشوند(بعضی مواقع از آن بنام نسبی یاد می کنند که غلط است وشامل انواع واقسام پدیده های مذهبی ، هنری ، حوادث طبیعی ، اقتصادی وغیره میباشد ، اینها بر اساس افهام عمومی واینکه تا چه قدر از بصیرت وعمق بینی برخوردار است می تواند سهوی ، موهومی ویا یک جریان حقیقی وپایدار باشد، استادی که یک عمر با مفروضات اقتصاد کلاسیک ونئو کلاسیک درس اقتصاد داده است ، این مرور واستمرار دائمی او ، اگر با تحقیق وعمق نگری وشرایط متغییر اوضاع بحق جهانی تقویت نشود ، تبدیل بیک مذهب واعتقاد میشود واطلاعات ، داده های آماری ونرم افزار قدیمی ، اورا به غلط فهمی از ظواهر پدیده ها میکشاند ، باین چنین فهمی میگویند سهوی ، وبه چنین آنالیزی نباید اعتماد کرد ودستور کا ر از آن استنتاج نمود ، چون وزنه ای سنگین اورا به قهقرا کشانده ویک لختی مخرب اورا در بر گرفته است واین یکی از رموز چاش های دنیاست.

35.The pity me seriously, while A project that as inertia their domination impose over other framework or social systems ,it changed To the dangerous and destruction , this subject is called as “Unintentional” (or proportional that is error too) and these beclouds as like: religious phenomena, artistic, natural disasters, economics and etc. These are based on public communication and that to do so is projected depth of insight can be unintentional, imaginary or be an truth flow is steady, a professor who has reached a lifetime with the assumptions of classical economics and new classical, t there is no deep thinking and research his review continues his constant be changed to a gilt and its belief and if there is no deep thinking and research and things variable universal truth conditions , therefore, information , statistical data and old software leads him to the misunderstanding of appearances phenomena, for this understanding say such an “Unintentional” and such analysis should not be trusted and the agenda concluded its work ,because of the heavy weight brought him to regress and wake destructive inertia that surrounds him, and this is one of the secrets about many challenges in the world.

.36 از مشکلات زمان ما ، کمبود مفسران حقیقی ، مذاکره کنندگان جویای حق ، رایزان های ورزیده برای اقناع طرف مقابل بوده تاضدیت گرائی (*antagonism.*) و بدفهمی ها از این قبیل رفع شود وموجب هدر دادن فرصت ها ومنافع خودشان نشود ، با ورود به عرصه جدید دانش مفید وآموزش دادن قواعد آن به مربیان ومسئولین جوامع بشری ، پا به میدان جدیدی از این جهان هستی بگذاریم ، به عنوان مثال ، اکثر کسانی که از غرب علیه جمهوری اسلامی ایران نقشه های شوم میکشند ، وهم های این چنین را براساس مذهب وراهبردهای تقلیدی خود دنبال میکنند ، درحالیکه با یک چرخش صحیح وعقلائی ، منافع غیر باور کردنی ای نصیب خودشان خواهد ساخت (به دوره حکومت صدام ودوره حاضر توجه کنیدوپول های که آمریکا بر اساس وهم خودش از دست داده بنگرید که هنوز هم در اوهام بسر میبرد).

37.The problems of our time there are : lack of truth interpreters , negotiators seeking the right, skilled advisors for persuading the other side till remedying of antagonism and misunderstanding of such these and Causing their own interests not to squander opportunities, we should arrive into the new world whit teaching of usefulness knowledge to educators and authorities societies, for example:most of those from the West who was designed against Iran, they mimic any groundless fear of imitative strategies based on their illuminates but with a proper rotation and reasonable survey, non-incredible benefits of their portion will (see to during the rule of Saddam and present courses and United States lost huge Dollars based on his own delusion that was still living in illusions)

.38بنابراین تنظیم وتدوین دکترین ها ، استراتژی ها ، سیاست ها وهدف گذاری در هر مورد ، ودر هر کشوری ، تغییرات شگفتی نموده است که ورود معلومات جدید، رویه ها ، اعتقادات وغور وبررسی مجدد در اندیشه وآثار دانشمندان حقیقت یاب ، راه نجات فعلی جهان است ، در غیر این صورت افول خودرا امضاء میکنند ، این یکی از ده ها دکترین من است .

39.So set regulation and codify of doctrines, strategies , policies and targeting has changed surprises in exceptional cases , in every countries , and new and exciting courses, procedures, and depth convictions re-examined and works on and effects works of truth scientists the current way to save the world, otherwise, they signed their decline and this is one of tens of mine doctrines.

40.شاعر : محمود صانعی پور

Poet: Mahmoud Saneipour

میرسد فریادی از دلِ سوزانِ بشر

نغمه ای دلسوز از ناجی ما،درسَحَر

آنکه نشنود این داد، از راه دور

بیگمان خواب است در هنگام سَحَر

It is arriving from the human, s inflaming heart

A sorrowfulness Song from our Savior at dawn

Whoever hears this burner from Long Distance?

He is sleeping when in dawn undoubtedly

ضمیمه: بخشی از تئوری های نیوتن

A part of newton’s theories (appendix)

From Wikipedia, the free encyclopedia

"Zero gravity" and "Zero-G" redirect here. For other uses, see Zero gravity (disambiguation).

Weightlessness, or an absence of weight, is an absence of stress and strain resulting from externally applied mechanical contact-forces, typically normal forces (from floors, seats, beds, scales, etc.). Counterintuitively, a uniform gravitational field does not by itself cause stress or strain, and a body in free fall in such an environment experiences no g-force acceleration and feels weightless. This is also termed **zero-g**, where the term is more correctly understood as meaning "zero g-force."

When bodies are acted upon by non-gravitational forces, as in a centrifuge, a rotating space station, or within a space ship with rockets firing, a sensation of weight is produced, as the contact forces from the moving structure act to overcome the body's inertia. In such cases, a sensation of weight, in the sense of a state of stress can occur, even if the gravitational field were zero. In such cases, g-forces are felt, and bodies are not weightless.

When the gravitational field is non-uniform, a body in free fall suffers tidal effects and is not stress-free. Near a black hole, such tidal effects can be very strong. In the case of the Earth, the effects are minor, especially on objects of relatively small dimension (such as the human body or a spacecraft) and the overall sensation of weightlessness in these cases is preserved. This condition is known as microgravity and it prevails in orbiting spacecraft.

In October 2015, the NASA Office of Inspector General issued a health hazards report related to human spaceflight, including a human mission to Mars.[1][2]

Weightlessness in Newtonian mechanics

In Newtonian mechanics the term "weight" is given two distinct interpretations by engineers.

Weight$_1$: Under this interpretation, the "weight" of a body is the gravitational force exerted on the body and this is the notion of weight that prevails in engineering. Near the surface of the earth, a body whose mass is 1 kg has a weight of approximately 9.81 N, independent of its state of motion, *free fall, or not*. Weightlessness in this sense can be achieved by removing the body far away from the source of gravity. It can also be attained by placing the body at a neutral point between two gravitating masses.

Weight$_2$: Weight can also be interpreted as that quantity which is measured when one uses scales. What is being measured there is the force exerted *by* the body on the scales. In a standard weighing operation, the body being weighed is in a state of equilibrium as a result of a force exerted on it by the weighing machine cancelling the gravitational field. By Newton's 3rd law, there is an equal and opposite force exerted *by* the body on the machine. *This* force is called weight$_2$. The force is *not* gravitational. Typically, it is a contact force and not uniform across the mass of the body. If the body is placed on the scales in a lift (an elevator) in free fall in pure uniform gravity, the scale would read zero, and the body said to be weightless i.e. its weight$_2$ = 0. This describes the condition in which the body is stress free and unreformed. This is the weightlessness in *free fall in a uniform gravitational field*. (The situation is more complicated when the gravitational field is not uniform, or, when a body is subject to multiple forces which may, for instance, cancel each other and produce a state of stress albeit weight$_2$ being zero. See below.)

To sum up, we have two notions of weight of which weight$_1$ are dominant. Yet 'weightlessness' is typically exemplified not by absence of weight$_1$ but by the absence of stress associated with weight$_2$. This is the intended sense of weightlessness in what follows below

A body is stress free, exerts zero weight$_2$, when the only force acting on it is weight$_1$ as when in free fall in a uniform gravitational field. Without subscripts, one ends up with the odd-sounding conclusion that **a body is weightless when the only force acting on it is its weight.**

The apocryphal apple that fell on Newton's head can be used to illustrate the issues involved. An apple weighs approximately 1 newton. This is the weight$_1$ of the apple and is considered to be a constant even while it is falling. During that fall, its weight$_2$ however is zero: ignoring air resistance, the apple is stress free. When it hits Newton, the sensation felt by Newton would depend upon the height from which the apple falls and weight$_2$ of the apple at the moment of impact may be many times greater than 1 N. It was great enough—in the story—to make the great man invent the theory of gravity. It is this weight$_2$ which distorts the apple. On its way down, the apple in its free fall does not suffer any distortion as the gravitational field is uniform

Stress during free fall

1. In a uniform gravitational field: Consider any cross-section dividing the body into two parts. Both parts have the same acceleration and the force exerted on each is supplied by the external source of the field. There is no force exerted by one part on the other. Stress at the cross-section is zero. Weight$_2$ is zero.

2. In a non-uniform gravitational field: Under gravity alone, one part of the body may have a different acceleration from another part. This would tend to

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deform the body and generate internal stresses if the body resists deformation. $Weight_2$ is not 0.

Throughout this discussion on using stress as an indicator of weight, any *pre-stress* which may exist within a body caused by a force exerted on one part by another is not relevant. The only relevant stresses are those generated by *external* forces applied to the body.

The definition and use of 'weightlessness' is difficult unless it is understood that the sensation of "weight" in everyday terrestrial experience results not from gravitation acting alone (which is not felt), but instead by the mechanical forces that resist gravity. An object in a straight free fall, or in a more complex inertial trajectory of free fall (such as within a reduced gravity aircraft or inside a space station), all experience weightlessness, since they do not experience the mechanical forces that cause the sensation of weight.

Force fields other than gravity

As noted above, weightlessness occurs when

1. no resultant force acts on the object
2. Uniform gravity acts solely by itself.

For the sake of completeness, a 3rd minor possibility has to be added. This is that a body may be subject to a field which is not gravitational but such that the force on the object is *uniformly distributed* across the object's **mass.** An electrically charged body, uniformly charged, in a uniform electric field is a possible example. Electric charge here replaces the usual gravitational charge. Such a body would then be stressing free and be classed as weightless. Various types of levitation may fall into this category, at least approximately

Weightlessness and proper acceleration

A body in free fall (which by definition entails no aerodynamic forces) near the surface of the earth has an acceleration approximately equal to 9.8 m s^{-2} with respect to a coordinate frame tied to the earth. If the body is in a freely falling lift and subject to no pushes or pulls from the lift or its contents, the acceleration with

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respect to the lift would be zero. If on the other hand, the body is subject to forces exerted by other bodies within the lift, it will have acceleration with respect to the freely falling lift. This acceleration which is not due to gravity is called "proper acceleration". On this approach, weightlessness holds when proper acceleration is zero…..

How to avoid weightlessness

Weightlessness is in contrast with current human experiences in which a non-uniform force is acting, such as:

- standing on the ground, sitting in a chair on the ground, etc., where gravity is countered by the support force of the ground,
- flying in a plane, where a support force is transmitted from the lift the wings provide (special trajectories which form an exception are described below),
- during atmospheric reentry, or during the use of a parachute, when atmospheric drag decelerates a vehicle,
- During an orbital maneuver in a spacecraft, or during the launch phase, when rocket engines provide thrust.

In cases where an object is not weightless, as in the above examples, a force acts non-uniformly on the object in question. Aero-dynamic lift, drag, and thrust are all non-uniform forces (they are applied at a point or surface, rather than acting on the entire mass of an object), and thus create the phenomenon of weight. This non-uniform force may also be transmitted to an object at the point of contact with a second object, such as the contact between the surface of the Earth and one's feet, or between a parachute harness and one's body.

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Micro-g environment

From Wikipedia, the free encyclopedia

(Redirected from Microgravity)

The International Space Station in orbit around Earth, February 2010. The ISS is in a **micro-g environment**.

The term **micro-g environment** (also **μg**, often referred to by the term **microgravity**) is more or less a synonym for *weightlessness* and *zero-g*, but indicates that g-forces are not quite zero, just very small.[1] The symbol for microgravity, *μg*, was used on the insignias of Space Shuttle flights STS-87 and STS-107, because these flights were devoted to microgravity research in low Earth orbit.

Tidal forces

Two rigid cubes joined by an elastic string in free fall near a black hole. The string stretches as the body falls to the right.

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Tidal forces arise when the gravitational field is not uniform and *gravitation gradients* exist. Such indeed is the norm and strictly speaking any object of finite size even in free-fall is subject to tidal effects. These are impossible to remove by inertial motion, except at one single nominated point of the body. The Earth is in free fall but the presence of tides indicates that it is in a non-uniform gravitational field. This non-uniformity is more due to the moon than the sun. The total gravitational field due to the sun is much stronger than that of the moon but it has a minor tidal effect compared with that of the moon because of the relative distances involved. Weight$_1$ of the earth is essentially due to the sun's gravity. But its state of stress and deformation, represented by the tides, is more due to non uniformity in the gravitational field of the nearby moon. When the size of a region being considered is small relative to its distance from the gravitating mass the assumption of uniform gravitational field holds to a good approximation. Thus a person is small relative to the radius of Earth and the field for a person at the surface of the earth is approximately uniform. The field is strictly not uniform and is responsible for the phenomenon of microgravity. Objects near a black hole are subject to a highly non-uniform gravitational field.

Frames of reference[1]

In all inertial reference frames, while weightlessness is experienced, Newton's first law of motion is obeyed locally *within the frame*. Inside the frame (for example, inside an orbiting ship or free-falling elevator), unforced objects keep their velocity relative to the frame. Objects not in contact with other objects "float" freely. If the inertial trajectory is influenced by gravity, the reference frame will be an accelerated frame as seen from a position outside the gravitational attraction, and (seen from far away) the objects in the frame (elevator, etc.) will appear to be under the influence of a force (the so-called force of gravity). As noted, objects subject solely to gravity do not feel its effects. Weightlessness can thus be realised for short periods of time in an airplane following a specific elliptic flight path, often mistakenly called a parabolic flight. It is simulated poorly, with many differences, in neutral buoyancy conditions, such as immersion in a tank of water.

Frames of reference 2

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Zero-g, "zero gravity", accelerometers[edit]

Zero-g is an alternative term for weightlessness and holds for instance in a freely falling lift. Zero-g is subtly different from the complete absence of gravity, something which is impossible due to the presence of gravity everywhere in the universe. "Zero-gravity" may also be used to mean effective weightlessness, neglecting tidal effects. *Microgravity* (or *µg*) is used to refer to situations that are substantially weightless but where g-force stresses within objects due to tidal effects, as discussed above, are around a millionth of that at the Earth's surface. Accelerometers can only detect g-force i.e. $weight_2$ (= mass × proper acceleration). They cannot detect the acceleration associated with free fall.[b]

Sensation of weight[edit]

The force on the feet is approximately double that on the cross-section through the navel.

Humans experience their own body weight as a result of this supporting force, which results in a normal force applied to a person by the surface of a supporting object, on which the person is standing or sitting. In the absence of this force, a person would be in free-fall, and would experience weightlessness. It is the transmission of this reaction force through the human body, and the

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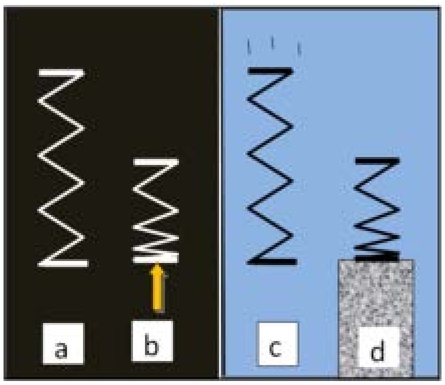
resultant compression and tension of the body's tissues, that results in the sensation of weight.

Because of the distribution of mass throughout a person's body, the magnitude of the reaction force varies between a person's feet and head. At any horizontal cross-section of a person's body (as with any column), the size of the compressive force being resisted by the tissues below the cross-section is equal to the weight of the portion of the body above the cross-section. In the pose adopted in the accompanying illustration, the shoulders carry the weight of the outstretched arms and are subject to a considerable torque.

Weightlessness in Newtonian mechanics [edit]



In the left half, the spring is far away from any gravity source. In the right half, it is in a uniform gravitation field. **a**) Zero gravity and weightless **b**) Zero gravity but not weightless (Spring is rocket propelled) **c**) Spring is in free fall and weightless **d**) Spring rests on a plinth and has both $weight_1$ and $weight_2$.

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A body is stress free, exerts zero weight$_2$, when the only force acting on it is weight$_1$ as when in free fall in a uniform gravitational field. Without subscripts, one ends up with the odd-sounding conclusion that **a body is weightless when the only force acting on it is its weight.**

The apocryphal apple that fell on Newton's head can be used to illustrate the issues involved. An apple weighs approximately 1 newton. This is the weight$_1$ of the apple and is considered to be a constant even while it is falling. During that fall, its weight$_2$ however is zero: ignoring air resistance, the apple is stress free. When it hits Newton, the sensation felt by Newton would depend upon the height from which the apple falls and weight$_2$ of the apple at the moment of impact may be many times greater than 1 N. It was great enough—in the story—to make the great

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man invent the theory of gravity. It is this weight$_2$ which distorts the apple. On its way down, the apple in its free fall does not suffer any distortion as the gravitational field is uniform.

Stress during free fall[edit]

1. In a uniform gravitational field: Consider any cross-section dividing the body into two parts. Both parts have the same acceleration and the force exerted on each is supplied by the external source of the field. There is no force exerted by one part on the other. Stress at the cross-section is zero. Weight$_2$ is zero.

2. In a non-uniform gravitational field: Under gravity alone, one part of the body may have a different acceleration from another part. This would tend to deform the body and generate internal stresses if the body resists deformation. Weight$_2$ is not 0.

Throughout this discussion on using stress as an indicator of weight, any *pre-stress* which may exist within a body caused by a force exerted on one part by another is not relevant. The only relevant stresses are those generated by *external* forces applied to the body.

The definition and use of 'weightlessness' is difficult unless it is understood that the sensation of "weight" in everyday terrestrial experience results not from gravitation acting alone (which is not felt), but instead by the mechanical forces that resist gravity. An object in a straight free fall, or in a more complex inertial trajectory of free fall (such as within a reduced gravity aircraft or inside a space station), all experience weightlessness, since they do not experience the mechanical forces that cause the sensation of weight.

Force fields other than gravity[edit]

As noted above, weightlessness occurs when

1. no resultant force acts on the object

2. uniform gravity acts solely by itself.

For the sake of completeness, a 3rd minor possibility has to be added. This is that a body may be subject to a field which is not gravitational but such that the force on the object is *uniformly distributed* across the object's mass. An electrically charged body, uniformly charged, in a uniform electric field is a possible example. Electric charge here replaces the usual gravitational charge. Such a body would then be stress free and be classed as weightless. Various types of levitation may fall into this category, at least approximately.

Weightlessness and proper acceleration[edit]

A body in free fall (which by definition entails no aerodynamic forces) near the surface of the earth has an acceleration approximately equal to 9.8 m s^{-2} with respect to a coordinate frame tied to the earth. If the body is in a freely falling lift and subject to no pushes or pulls from the lift or its contents, the acceleration with respect to the lift would be zero. If on the other hand, the body is subject to forces exerted by other bodies within the lift, it will have an acceleration with respect to the freely falling lift. This acceleration which is not due to gravity is called "proper acceleration". On this approach, weightlessness holds when proper acceleration is zero.

How to avoid weightlessness[edit]

Weightlessness is in contrast with current human experiences in which a non-uniform force is acting, such as:

- standing on the ground, sitting in a chair on the ground, etc., where gravity is countered by the support force of the ground,
- flying in a plane, where a support force is transmitted from the lift the wings provide (special trajectories which form an exception are described below),
- during atmospheric reentry, or during the use of a parachute, when atmospheric drag decelerates a vehicle,
- during an orbital maneuver in a spacecraft, or during the launch phase, when rocket engines provide thrust.

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In cases where an object is not weightless, as in the above examples, a force acts non-uniformly on the object in question. Aero-dynamic lift, drag, and thrust are all non-uniform forces (they are applied at a point or surface, rather than acting on the entire mass of an object), and thus create the phenomenon of weight. This non-uniform force may also be transmitted to an object at the point of contact with a second object, such as the contact between the surface of the Earth and one's feet, or between a parachute harness and one's body.

A geostationary satellite above a marked spot on the Equator. An observer on the marked spot will see the satellite remain directly overhead unlike the other heavenly objects which sweep across the sky.

Spacecraft are held in orbit by the gravity of the planet which they are orbiting. In Newtonian physics, the sensation of weightlessness experienced by astronauts is not the result of there being zero gravitational acceleration (as seen from the Earth), but of there being no g-force that an astronaut can feel because of the free-fall condition, and also there being zero difference between the acceleration of the spacecraft and the acceleration of the astronaut. Space journalist James Oberg explains the phenomenon this way:[3]

The myth that satellites remain in orbit because they have "escaped Earth's gravity" is perpetuated further (and falsely) by almost universal misuse of the word "zero gravity" to describe the free-falling conditions aboard orbiting space vehicles. Of course, this isn't true; gravity still exists in space. It keeps satellites from flying straight off into interstellar emptiness. What's missing is "weight", the resistance of gravitational attraction by an anchored structure or a counterforce. Satellites stay in space because of their tremendous horizontal speed, which allows them—while being unavoidably pulled toward Earth by gravity—to fall "over the horizon." The ground's curved withdrawal along the Earth's round surface offsets the satellites' fall toward the ground. Speed, not position or lack of gravity, keeps satellites in orbit around the earth.

A geostationary satellite is of special interest in this context. Unlike other objects in the sky which rise and set, an object in a geostationary orbit appears motionless in the sky, apparently defying gravity. In fact, it is in a circular equatorial orbit with a period of one day.

Relativity[edit]

To a modern physicist working with Einstein's general theory of relativity, the situation is even more complicated than is suggested above. Einstein's theory suggests that it actually is valid to consider that objects in inertial motion (such as falling in an elevator, or in a parabola in an airplane, or orbiting a planet) can indeed be considered to experience a local loss of the gravitational field in their rest frame. Thus, in the point of view (or frame) of the astronaut or orbiting ship, there actually is nearly-zero proper acceleration (the acceleration felt locally), just as would be the case far out in space, away from any mass. It is thus valid to consider that most of the gravitational field in such situations is actually absent from the point of view of the falling observer, just as the colloquial view suggests (see equivalence principle for a fuller explanation of this point). However, this loss of gravity for the falling or orbiting observer, in Einstein's theory, is due to the falling motion itself, and (again as in Newton's theory) not due to increased distance from the Earth. However, the gravity nevertheless is considered to be absent. In fact, Einstein's realization that a pure gravitational interaction cannot be felt, if all other forces are removed, was the key insight to leading him to the view that the gravitational "force" can in some ways be viewed as non-existent. Rather, objects tend to follow geodesic paths in curved space-time, and this is "explained" as a force, by "Newtonian" observers who assume that space-time is "flat," and thus do not have a reason for curved paths (i.e., the "falling motion" of an object near a gravitational source).

In the theory of general relativity, the only gravity which remains for the observer following a falling path or "inertial" path near a gravitating body, is that which is due to non-uniformities which remain in the gravitational field, even for the falling observer. This non-uniformity, which is a simple tidal effect in Newtonian dynamics, constitutes the "microgravity" which is felt by all spacially-extended objects falling in any natural gravitational field that originates from a compact mass. The reason for these tidal effects is that such a field will have its origin in a centralized place (the compact mass), and thus will diverge, and vary slightly in strength, according to distance from the mass. It will thus vary across the width of the falling or orbiting object. Thus, the term "microgravity," an overly technical term from the Newtonian view, is a valid and descriptive term in the general relativistic (Einsteinian) view.

Microgravity[edit]

Main article: Micro-g environment

The term **micro-g environment** (also ***μg***, often referred to by the term **microgravity**) is more or less a synonym of weightlessness and *zero-G*, but indicates that g-forces are not quite zero, just very small.[*citation needed*]

Weightless and reduced weight environments[edit]

Zero gravity flight maneuver

Reduced weight in aircraft [edit]

Main article: Reduced gravity aircraft

Airplanes have been used since 1959 to provide a nearly weightless environment in which to train astronauts, conduct research, and film motion pictures. Such aircraft are commonly referred by the nickname "Vomit Comet".To create a weightless environment, the airplane flies in a six-mile long parabolic arc, first climbing, then entering a powered dive. During the arc, the propulsion and steering of the aircraft are controlled such that the drag (air resistance) on the plane is cancelled out, leaving the plane to behave as it would if it were free-falling in a vacuum. During this period, the plane's occupants experience 22 seconds of weightlessness, before experiencing about 22 seconds of 1.8 *g* acceleration (nearly twice their normal weight) during the pull-out from the parabola. A typical flight lasts around two hours, during which 30 parabolae are flown.

NASA's KC-135A plane ascending for a zero gravity maneuver

NASA's Reduced Gravity Aircraft[edit]

Versions of such airplanes have been operated by NASA's Reduced Gravity Research Program since 1973, where the unofficial nickname originated.[4] NASA later adopted the official nickname 'Weightless Wonder' for publication.[5] NASA's current Reduced Gravity Aircraft, "Weightless Wonder VI", a McDonnell Douglas C-9, is based at Ellington Field (KEFD), near Lyndon B. Johnson Space Center.NASA's Microgravity University - Reduced Gravity Flight Opportunities Plan, also known as the Reduced Gravity Student Flight Opportunities Program, allows teams of undergraduates to submit a microgravity experiment proposal. If selected, the teams design and implement their experiment, and students are invited to fly on NASA's Vomit Comet.

European Space Agency A310 Zero-G

The European Space Agency flies parabolic flights on a specially-modified Airbus A310-300 aircraft,[6] in order to perform research in microgravity. As well European ESA, French CNES and German DLR fly *campaigns* of three flights on consecutive days, each flying about 30 parabolas, for a total of about 10 minutes of weightlessness per flight. These campaigns are currently operated from Bordeaux - Mérignac Airport in France by the company Novespace,[7] a subsidiary of French CNES, while the aircraft is flown by test pilots from DGA Essais en Vol. The first ESA Zero-G flights were in 1984, using a NASA KC-135 aircraft in Houston, Texas. As of May 2010, the ESA has flown 52 campaigns and also 9 student parabolic flight campaigns.[8]

Other aircraft it has used include the Russian Ilyushin Il-76 MDK before founding Novespace, and using then a French Caravelle, then an Airbus A300 Zero-G and now an Airbus A310 [9][10][11]

Commercial flights for public passengers[edit]

Novespace created Air Zero G in 2012 to share the experience of weightlessness to 40 public passengers per flight, using the same A310 ZERO-G than for scientific experiences.[12] These flights are sold by Avico, are mainly operated from Bordeaux-Merignac, France, and intend to promote European space research, allowing public passengers to feel weighlessness. Jean-François Clervoy, Chairman of Novespace and ESA astronaut, flies with Air Zero G one-day-astronauts on board A310 Zero-G. After the flight, he explains the quest of space and talks about the 3 space travels he did along his career. The aircraft has also been used for cinema purposes, with Tom Cruise and Annabelle Wallisfor the Mummy in 2017.[13]

The Zero Gravity Corporation, founded in 1993 by Peter Diamandis, Byron Lichtenberg, and Ray Cronise, operates a modified Boeing 727 which flies parabolic arcs to create 25–30 seconds of weightlessness. Flights may be purchased for both tourism and research purposes.

Ground-based drop facilities[edit]

Zero-gravity testing at the NASA Zero Gravity Research Facility

Ground-based facilities that produce weightless conditions for research purposes are typically referred to as drop tubes or drop towers.

NASA's Zero Gravity Research Facility, located at the Glenn Research Center in Cleveland, Ohio, is a 145-meter vertical shaft, largely below the ground, with an integral vacuum drop chamber, in which an experiment vehicle can have a free fall for a duration of 5.18 seconds, falling a distance of 132 meters. The experiment vehicle is stopped in approximately 4.5 meters of pellets of expanded polystyrene and experiences a peak deceleration rate of 65g.

Also at NASA Glenn is the 2.2 Second Drop Tower, which has a drop distance of 24.1 meters. Experiments are dropped in a drag shield, in order to reduce the effects of air drag. The entire package is stopped in a 3.3 meter tall air bag, at a peak deceleration rate of approximately 20g. While the Zero Gravity Facility conducts one or two drops per day, the 2.2 Second Drop Tower can conduct up to twelve drops per day.

NASA's Marshall Space Flight Center hosts another drop tube facility that is 105 meters tall and provides a 4.6 second free fall under near-vacuum conditions.[14]

Humans cannot utilize these gravity shafts, as the deceleration experienced by the drop chamber would likely kill or seriously injure anyone using them; 20g is about the highest deceleration that a fit and healthy human can withstand momentarily without sustaining injury.[citation needed]

Other drop facilities worldwide include:

- Micro-Gravity Laboratory of Japan (MGLAB) – 4.5 s free fall
- Experimental drop tube of the metallurgy department of Grenoble – 3.1 s free fall
- Fallturm Bremen University of Bremen in Bremen – 4.74 s free fall
- Queensland University of Technology Drop Tower - 2.0 s free fall

Neutral buoyancy[edit]

Weightlessness can also be simulated by creating the condition of neutral buoyancy, in which human subjects and equipment are placed in a water environment and weighted or buoyed until they hover in place. NASA uses neutral buoyancy to prepare for extra-vehicular activity (EVA) at its Neutral Buoyancy Laboratory. Neutral buoyancy is also used for EVA research at the University of Maryland's Space Systems Laboratory, which operates the only neutral buoyancy tank at a college or university.

Neutral buoyancy is not identical to weightlessness. Gravity still acts on all objects in a neutral buoyancy tank; thus, astronauts in neutral buoyancy training still feel their full body weight within their spacesuits, although the weight is well-distributed, similar to force on a human body in a water bed, or when simply floating in water. The suit and astronaut together are under no net force, as for any object that is floating, or supported in water, such as a scuba diver at neutral buoyancy. Water also produces drag, which is not present in vacuum.

Weightlessness in a spacecraft[edit]

The relationship between acceleration and velocity vectors in an orbiting spacecraft

US astronaut Marsha Ivinsdemonstrates the effect of weightlessness on long hair during STS-98

Long periods of weightlessness occur on spacecraft outside a planet's atmosphere, provided no propulsion is applied and the vehicle is not rotating. Weightlessness does not occur when a spacecraft is firing its engines or when re-entering the atmosphere, even if the resultant acceleration is constant. The thrust provided by the engines acts at the surface of the rocket nozzle rather than acting uniformly on the spacecraft, and is transmitted through the structure of the spacecraft via compressive and tensile forces to the objects or people inside.

Weightlessness in an orbiting spacecraft is physically identical to free-fall, with the difference that gravitational acceleration causes a net change in the *direction*, rather than the *magnitude*, of the spacecraft's velocity. This is because the acceleration vector is perpendicular to the velocity vector.

In typical free-fall, the acceleration of gravity acts along the direction of an object's velocity, linearly increasing its speed as it falls toward the Earth, or slowing it down if it is moving away from the Earth. In the case of an orbiting spacecraft, which has a velocity vector largely *perpendicular* to the force of gravity, gravitational acceleration does not produce a net change in the object's speed, but instead acts centripetally, to constantly "turn" the spacecraft's velocity as it moves around the Earth. Because the acceleration vector turns along with the velocity vector, they remain perpendicular to each other. Without this change in the direction of its velocity vector, the spacecraft would move in a straight line, leaving the Earth altogether.

Weightlessness at the center of a planet[edit]

The net gravitational force due to a spherically symmetrical planet is zero at the center. This is clear because of symmetry, and also from Newton's shell theorem which states that the net gravitational force due to a spherically symmetric shell, e.g., a hollow ball, is zero anywhere inside the hollow space. Thus the material at the center is weightless.

Human health effects[edit]

Main articles: Effect of spaceflight on the human body and Space medicine

Astronaut Clayton Anderson as a water bubble floats in front of him on the Discovery. Cohesion plays a bigger role in space.

Following the advent of space stations that can be inhabited for long periods, exposure to weightlessness has been demonstrated to have some deleterious effects on human health.[15] Humans are well-adapted to the physical conditions at the surface of the Earth. In response to an extended period of weightlessness, various physiological systems begin to change and atrophy. Though these changes are usually temporary, long term health issues can result.

The most common problem experienced by humans in the initial hours of weightlessness is known as space adaptation syndrome or SAS, commonly referred to as space sickness. Symptoms of SAS include nausea and vomiting, vertigo, headaches, lethargy, and overall malaise.[16] The first case of SAS was reported by cosmonaut Gherman Titov in 1961. Since then, roughly 45% of all people who have flown in space have suffered from this condition. The duration of space sickness varies, but in no case has it lasted for more than 72 hours, after which the body adjusts to the new environment. NASA jokingly measures SAS using the "Garn scale", named for United States Senator Jake Garn, whose SAS during STS-51-D was the worst on record. Accordingly, one "Garn" is equivalent to the most severe possible case of SAS.[17]

The most significant adverse effects of long-term weightlessness are muscle atrophy (see Reduced muscle mass, strength and performance in space for more information) and deterioration of the skeleton, or spaceflight osteopenia.[16] These effects can be minimized through a regimen of exercise such as cycling for example. Astronauts subject to long periods of weightlessness wear pants with elastic bands attached between waistband and cuffs to compress the leg bones and reduce osteopenia.[18] Other significant effects include fluid redistribution (causing the "moon-face" appearance typical of pictures of astronauts in weightlessness),[18][19] a slowing of the cardiovascular systemas blood flow decreases in response to a lack of gravity,[20] a decreased production of red blood cells, balance disorders, and a weakening of the immune system. Lesser symptoms include loss of body mass, nasal congestion, sleep disturbance, excess flatulence, and puffiness of the face. These effects begin to reverse quickly upon return to the Earth.

In addition, after long space flight missions, astronauts may experience severe eyesight problems.[21][22][23][24][25] Such eyesight problems may be a major concern for future deep space flight missions, including a manned mission to the planet Mars.[21][22][23][24][26] Exposure to high levels of radiation may influence the development of atherosclerosis also.[27]

On December 31, 2012, a NASA-supported study reported that manned spaceflight may harm the brains of astronauts and accelerate the onset of Alzheimer's disease.[28][29][30]

Effects on non-human organisms[edit]

Main articles: Effect of spaceflight on the human body, Infection, Medical treatment during spaceflight, and Space medicine

Russian scientists have observed differences between cockroaches conceived in space and their terrestrial counterparts. The space-conceived cockroaches grew more quickly, and also grew up to be faster and tougher.[31]

Chicken eggs that are put in microgravity two days after fertilization appear not to develop properly, whereas eggs put in microgravity more than a week after fertilization develop normally.[32]

A 2006 Space Shuttle experiment found that *Salmonella typhimurium*, a bacterium that can cause food poisoning, became more virulent when cultivated in space.[33] On April 29, 2013, scientists in Rensselaer Polytechnic Institute, funded by NASA, reported that, during spaceflight on the International Space Station, microbes seem to adapt to the space environment in ways "not observed on Earth" and in ways that "can lead to increases in growth and virulence".[34]

Under certain test conditions, microbes have been observed to thrive in the near-weightlessness of space[35] and to survive in the vacuum of outer space.[36][37]

Tehnical adaptation in zero-gravity[edit]

Candle flame in orbital conditions (right) versus on Earth (left)

Weightlessness can cause serious problems on technical instruments, especially those consisting of many mobile parts. Physical processes that depend on the weight of a body (like convection, cooking water or burning candles) act differently in free-fall. Cohesion and advection play a bigger role in space. Everyday work like washing or going to the bathroom are not possible without adaptation. To use toilets in space, like the one on the International Space Station, astronauts have to fasten themselves to the seat. A fan creates suction so that the waste is pushed away. Drinking is aided with a straw or from tubes.

1. **Jump up^** In General Relativity, GR, a body is inertial if it is in free fall i.e. it has no forces acting on it. Gravity is not a force in GR. Inertial bodies can be in a state of acceleration with respect to each other unlike in Newtonian physics where all inertial frames move at a constant velocity with respect to each other.
2. **Jump up^** Note: Accelerometers can detect a sudden *change* to free fall (as when a device is dropped), but they do this by measuring the change of acceleration from some value to zero. An accelerometer using a single weight or vibrating element and not measuring gradients across distances

inside the accelerometer (which could be used to detect microgravity or tidal forces), cannot tell the difference between free fall in a gravity field, and weightlessness due to being far from masses and sources of gravitation. This is due to Einstein's strong equivalence principle.

References[edit]

Lift (force)

From Wikipedia, the free encyclopedia

For other uses, see Lift (disambiguation).

The wings of the Boeing 747-8F generate many tonnes of lift.

A fluid flowing past the surface of a body exerts a force on it. **Lift** is the component of this force that is perpendicular to the oncoming flow direction.[1] It contrasts with the drag force, which is the component of the surface force parallel to the flow direction. Lift conventionally acts in an upward direction in order to counter the force of gravity, but it can act in any direction at right angles to the flow.

If the surrounding fluid is air, the force is called an aerodynamic force. In water or any other liquid, it is called a hydrodynamic force.

Dynamic lift is distinguished from other kinds of lift in fluids. Aerostatic lift or buoyancy, in which an internal fluid is lighter than the surrounding fluid, does not require movement and is used by balloons, blimps, dirigibles, boats, and submarines. Planing lift, in which only the lower portion of the body is immersed in a liquid flow, is used by motorboats, surfboards, and water-skis.

Overview[edit]

Lift is defined as the component of the total aerodynamic force perpendicular to the flow direction, and drag is the component parallel to the flow direction.

A fluid flowing over the surface of a body exerts a force on it. It makes no difference whether the fluid is flowing past a stationary body or the body is moving through a stationary volume of fluid. **Lift** is the component of this force that is perpendicular to the oncoming flow direction.[2] Lift is always accompanied by a drag force, which is the component of the surface force parallel to the flow direction.

Lift is most commonly associated with the wings of fixed-wing aircraft, although it is more generally generated by many other streamlined bodies such as propellers, kites, helicopter rotors, racing car wings, maritime sails and wind turbines in air, and by sailboat keels, ship's rudders and hydrofoils in water. Lift is also exploited in the animal world, especially by birds, bats and insects, and even in the plant world by the seeds of certain trees.[3]

While the common meaning of the word "lift" assumes that lift opposes weight, lift in general can technically be in any direction with respect to gravity, since it is defined with respect to the direction of flow rather than to the direction of gravity. When an aircraft is cruising in straight and level flight, most of the lift opposes gravity.[4] However, when an aircraft is climbing, descending, or banking in a turn the lift is tilted with respect to the vertical.[5] Lift may also act as downforce in some aerobatic manoeuvres, or on the wing on a racing car. Lift may also be largely horizontal, for instance on a sailing ship.

The Lift discussed in this article is mainly in relation to airfoils, although marine hydrofoils and propellers share the same physical principles and work in the same way, despite differences between air and water such as density, compressibility, and viscosity.

Simplified physical explanations of lift on an airfoil[edit]

A cross-section of a wing defines an airfoil shape

An airfoil is a streamlined shape that is capable of generating significantly more lift than drag.[6] A flat plate can generate lift, but not as much as a streamlined airfoil, and with somewhat higher drag.

There are several ways to explain how an airfoil generates lift. Some are more complicated or more mathematically rigorous than others; some have been shown to be incorrect.[7][8][9][10][11] For example, there are explanations based directly on Newton’s laws of motion and explanations based on Bernoulli’s principle. Either can be used to explain lift.[12][13]

Flow deflection and Newton's laws[edit]

When an airfoil deflects air downwards, Newton's third law requires that the air must exert an equal upward reaction on the airfoil.

An airfoil generates lift by exerting a downward force on the air as it flows past. According to Newton's third law, the air must exert an equal and opposite (upward) force on the airfoil, which is the lift.[14][15][16][17]

The air flow changes direction as it passes the airfoil and follows a path that is curved downward. According to Newton's second law, this change in flow direction requires a downward force applied to the air by the airfoil. Then, according to Newton's third law, the air must exert an upward force on the airfoil. The overall result is that a reaction force, the lift, is generated opposite to the directional change. In the case of an airplane wing, the wing exerts a downward force on the air and the air exerts an upward force on the wing.[18][19][20][21][22][23]

The downward turning of the flow is not produced solely by the lower surface of the airfoil, and the air flow above the airfoil accounts for much of the downward-turning action.

Increased flow speed and Bernoulli's principle[edit]

Bernoulli's principle states that within a steady airflow of constant energy, when the air flows through a region of lower pressure it speeds up and vice versa.[24] Thus, there is a direct mathematical relationship between the pressure and the speed, so if one knows the speed at all points within the airflow one can calculate the pressure, and vice versa. For any airfoil generating lift, there must be a pressure imbalance, i.e. lower average air pressure on the top than on the bottom. Bernoulli's principle states that this pressure difference must be accompanied by a speed difference.

Conservation of mass[edit]

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Streamlines and streamtubes around an airfoil generating lift. Note the narrower streamtubes above and the wider streamtubes above.

Starting with the flow pattern observed in both theory and experiments, the increased flow speed over the upper surface can be explained in terms of streamtube pinching and conservation of mass.[25]

Assuming that the air is incompressible, the rate of volume flow (e.g. liters or gallons per minute) must be constant within each streamtube since matter is not created or destroyed. If a streamtube becomes narrower, the flow speed must increase in the narrower region to maintain the constant flow rate. This is an application of the principle of conservation of mass.[26]

The upper stream tubes constrict as they flow up and around the airfoil. Conservation of mass says that the flow speed must increase as the stream tube area decreases.[25] Similarly, the lower stream tubes expand and the flow slows down.

From Bernoulli's principle, the pressure on the upper surface where the flow is moving faster is lower than the pressure on the lower surface where it is moving slower. This pressure difference creates a net aerodynamic force, pointing upward.

Limitations of explanations based on Bernoulli's principle[edit]

- The explanation above does not explain why the streamtubes change size. To see why the air flows the way it does requires more sophisticated analysis.[27][28][29]
- Sometimes a geometrical argument is offered to demonstrate why the streamtubes change size: it is asserted that the top "obstructs" or "constricts" the air more than the bottom, hence narrower streamtubes. For conventional wings that are flat on the bottom and curved on top this makes some intuitive sense. But it does not explain how flat plates, symmetric airfoils, sailboat sails, or conventional airfoils flying upside down can generate lift, and attempts to calculate lift based on the amount of constriction do not predict experimental results.[30][31][32][33]

- A common explanation using Bernoulli's principle asserts that the air must traverse both the top and bottom in the same amount of time and that this explains the increased speed on the (longer) top side of the wing. But this assertion is false; it is typically the case that the air parcels traveling over the upper surface will reach the trailing edge before those traveling over the bottom.[34]

Basic attributes of lift[edit]

Lift is a result of pressure differences and depends on angle of attack, airfoil shape, air density, and airspeed.

Pressure differences[edit]

Pressure is the normal force per unit area exerted by the air on itself and on surfaces that it touches. The lift force is transmitted through the pressure, which acts perpendicular to the surface of the airfoil. The air maintains physical contact at all points. Thus, the net force manifests itself as pressure differences. The direction of the net force implies that the average pressure on the upper surface of the airfoil is lower than the average pressure on the underside.[35]

These pressure differences arise in conjunction with the curved air flow. Whenever a fluid follows a curved path, there is a pressure gradient perpendicular to the flow direction with higher pressure on the outside of the curve and lower pressure on the inside.[36] This direct relationship between curved streamlines and pressure differences was derived from Newton's second law by Leonhard Euler in 1754:

The left hand side of this equation represents the pressure difference perpendicular to the fluid flow. On the right hand side ρ is the density, v is the velocity, and R is the radius of curvature. This formula shows that higher velocities and tighter curvatures create larger pressure differentials and that for straight flow ($R \to \infty$) the pressure difference is zero.[37]

Angle of attack[edit]

Angle of attack of an airfoil

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The angle of attack is the angle between the chord line of an airfoil and the oncoming air. A symmetrical airfoil will generate zero lift at zero angle of attack. But as the angle of attack increases, the air is deflected through a larger angle and the vertical component of the airstream velocity increases, resulting in more lift. For small angles a symmetrical airfoil will generate a lift force roughly proportional to the angle of attack.[38][39]

As the angle of attack grows larger, the lift reaches a maximum at some angle; increasing the angle of attack beyond this critical angle of attack causes the upper-surface flow to separate from the wing; there is less deflection downward so the airfoil generates less lift. The airfoil is said to be stalled.[40]

Airfoil shape[edit]

An airfoil with camber compared to a symmetrical airfoil

The lift force depends on the shape of the airfoil, especially the amount of camber (curvature such that the upper surface is more convex than the lower surface, as illustrated at right). Increasing the camber generally increases lift.[41][42]

Cambered airfoils will generate lift at zero angle of attack. When the chord line is horizontal, the trailing edge has a downward direction and since the air follows the trailing edge it is deflected downward.[43] When a cambered airfoil is upside down, the angle of attack can be adjusted so that the lift force is upwards. This explains how a plane can fly upside down.[44][45]

Flow conditions[edit]

The ambient flow conditions which affect lift include the fluid density, viscosity and speed of flow. Lift is proportional to the density of the fluid and approximately proportional to the square of the flow speed. The density, in its turn, may be affected by temperature and, at high speeds approaching or exceeding the speed of sound in the fluid, by compressibility effects. Lift also depends on the size of the wing, being generally proportional to the wing's area projected in the lift direction.

Air speed and density[edit]

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The flow conditions also affect lift. Lift is proportional to the density of the air and approximately proportional to the square of the flow speed. Lift also depends on the size of the wing, being generally proportional to the wing's area projected in the lift direction. In aerodynamic theory and engineering calculations it is often convenient to quantify lift in terms of a "Lift coefficient" defined in a way that makes use of these proportionalities.

A more comprehensive physical explanation[edit]

As described above, there are two main popular explanations of lift: one based on downward deflection of the flow (Newton's laws), and one based on pressure differences accompanied by changes in flow speed (Bernoulli's principle). Either of these, by itself, correctly identifies some aspects of the lifting flow but leaves other important aspects of the phenomenon unexplained. A more comprehensive explanation involves both downward deflection and pressure differences (including changes in flow speed associated with the pressure differences), and requires looking at the flow in more detail.[46]

Lift at the airfoil surface [edit]

The airfoil shape and angle of attack work together so that the airfoil exerts a downward force on the air as it flows past. According to Newton's third law, the air must then exert an equal and opposite (upward) force on the airfoil, which is the lift.[15][16]

The net force exerted by the air occurs as a pressure difference over the airfoil's surfaces.[47] Pressure in a fluid is always positive in an absolute sense,[48] so that pressure must always be thought of as pushing, and never as pulling. The pressure thus pushes inward on the airfoil everywhere on both the upper and lower surfaces. The flowing air reacts to the presence of the wing by reducing the pressure on the wing's upper surface and increasing the pressure on the lower surface. The pressure on the lower surface pushes up harder than the reduced pressure on the upper surface pushes down, and the net result is upward lift.[47]

The pressure difference that exerts lift acts directly on the airfoil surfaces. But understanding how the pressure difference is produced requires understanding what the flow does over a wider area.

The wider flow around the airfoil[edit]

Flow around an airfoil: the dots move with the flow. The black dots are on time slices, which split into two – an upper and lower part – at the leading edge. A marked speed difference between the upper-and lower-surface streamlines is shown most clearly in the image animation, with the upper markers arriving at the trailing edge long before the lower ones. Colors of the dots indicate streamlines.

Pressure distribution with isobars around a lifting airfoil. The plus sign indicates pressure higher than ambient, and the minus sign indicates pressure lower than ambient (not negative pressure in the absolute sense). The block arrows indicate the directions of net forces on fluid parcels in different parts of the flowfield.

An airfoil affects the speed and direction of the flow over a wide area. When an airfoil produces lift, the flow ahead of the airfoil is deflected upward, the flow above and below the airfoil is deflected downward, and the flow behind the airfoil is eventually deflected upward again, leaving the air far behind the airfoil in the same state as the oncoming flow far ahead. The flow above the upper surface is sped up, while the flow below the airfoil is slowed down. Together with the upward deflection of air in front and the downward deflection of the air immediately behind, this establishes a net circulatory component of the flow. The downward deflection and the changes in flow speed are pronounced and extend over a wide area, as can be seen in the flow animation on the right. These differences in the direction and speed of the flow are greatest close to the airfoil and decrease gradually far above and below. All of these features of the velocity field also appear in theoretical models for lifting flows.[49][50]

The pressure is also affected over a wide area. When an airfoil produces lift, there is always a diffuse region of low pressure above the airfoil, and there is usually a diffuse region of high pressure below, as illustrated by the isobars (curves of constant pressure) in the drawing. The pressure difference that acts on the surface is just part of this spread-out pattern of non-uniform pressure.[46]

Mutual interaction of pressure differences and changes in flow velocity[edit]

The non-uniform pressure exerts forces on the air in the direction from higher pressure to lower pressure. The direction of the force is different at different locations around the airfoil, as indicated by the block arrows in the *pressure distribution with isobars*figure. Air above the airfoil is pushed toward the center of the low-pressure region, and air below the airfoil is pushed outward from the center of the high-pressure region.

According to *Newton's second law*, a force causes air to accelerate in the direction of the force. Thus the vertical arrows in the *pressure distribution with isobars* figure indicate that air above and below the airfoil is accelerated, or turned downward, and that the non-uniform pressure is thus the cause of the downward deflection of the flow visible in the flow animation. To produce this downward turning, the airfoil must have a positive angle of attack or have its rear portion curved downward as on an airfoil with camber. Note that the downward turning of the flow over the upper surface is the result of the air being pushed downward by higher pressure above it than below it.

The arrows ahead of the airfoil indicate that the flow ahead of the airfoil is deflected upward, and the arrows behind the airfoil indicate that the flow behind is deflected upward again, after being deflected downward over the airfoil. These deflections are also visible in the flow animation.

The arrows ahead of the airfoil and behind also indicate that air passing through the low-pressure region above the airfoil is sped up as it enters, and slowed back down as it leaves. Air passing through the high-pressure region below the airfoil sees the opposite: It is slowed down and then sped back up. Thus the non-uniform pressure is also the cause of the changes in flow speed visible in the flow animation. The changes in flow speed are consistent with *Bernoulli's principle*, which states that in a steady flow without viscosity, lower pressure means higher speed, and higher pressure means lower speed.

Thus changes in flow direction and speed are directly caused by the non-uniform pressure. But this cause-and-effect relationship is not just one-way; it works in both directions simultaneously. The air's motion is affected by the pressure differences, but the existence of the pressure differences depends on the air's motion. The relationship is thus a mutual, or reciprocal, interaction: Air flow changes speed or direction in response to pressure differences, and the pressure differences are sustained by the air's resistance to changing speed or direction.[51] A pressure difference can exist only if something is there for it to push against. In the case of an aerodynamic flow, what a pressure difference pushes against is the inertia of the air, as the air is accelerated by the pressure difference.[46] And this is why the mass of the air is important, and why lift depends on air density.

In summary, sustaining the pressure difference that exerts the lift force on the airfoil surfaces requires sustaining a pattern of non-uniform pressure spread over a wide area around the airfoil. This requires maintaining pressure differences in both the vertical and horizontal directions, and thus requires both downward turning of the flow and changes in flow speed according to Bernoulli's principle. The pressure differences and the changes in flow direction and speed sustain each other in a mutual interaction. The pressure differences follow naturally from Newton's second law and from the fact that the flow along the surface naturally follows the predominantly downward-sloping contours of the airfoil. And the fact that the air has mass is crucial to the interaction.[46]

Momentum balance[edit]

Illustration of the distribution of higher-than-ambient pressure on the ground under an airplane in flight

At some point, the downward momentum of the air in the wake must be counteracted by an upward force, in order to ensure that the net momentum change is zero. This force is supplied by the ground over which the airfoil is flying.

When it meets the ground, the downward-moving wake establishes a pattern of higher-than-ambient pressure, as shown on the right[52] For steady, level flight, the integrated pressure force associated with this pattern is equal to the total aerodynamic lift of the airplane and to the airplane's weight. According to Newton's third law, this pressure force exerted on the ground by the air is matched by an equal-and-opposite upward force exerted on the air by the ground, which offsets all of the downward force exerted on the air by the airplane. The net force due to the lift, acting on the atmosphere as a whole, is therefore zero, and there is thus no integrated accumulation of vertical momentum in the atmosphere.[53]

Boundary layer[edit]

Airflow separating from a wing at a high angle of attack

No matter how smooth the surface of an airfoil seems, any real surface is rough on the scale of air molecules. Air molecules flying into the surface bounce off the rough surface in random directions not related to their incoming directions. The result is that when the air is viewed as if it were a continuous material, it is seen to be unable to slide along the surface, and the air's tangential velocity at the surface goes to practically zero, something known as the no-slip condition.[54] Because the air at the surface has near-zero velocity, and air away from the surface is moving, there is a thin boundary layer in which the air close to the surface is subjected to a shearing motion.[55][56] The air's viscosity resists the shearing, giving rise to a shear stress at the airfoil's surface called skin-friction drag. Over most of the surface of most airfoils, the boundary layer is naturally turbulent, which increases skin-friction drag.[56][57]

Stalling[edit]

Under usual flight conditions, the boundary layer remains attached to both the upper and lower surfaces all the way to the trailing edge, and its effect on the rest of the flow is modest. Compared to the predictions of inviscid-flow theory, in which there is no boundary layer, the attached boundary layer reduces the lift by a modest amount and modifies the pressure distribution somewhat, which results in a viscosity-related pressure drag over and above the skin-friction drag. The total of the skin-friction drag and the viscosity-related pressure drag is usually called the profile drag.[57][58]

The maximum lift an airfoil can produce at a given airspeed is limited by boundary-layer separation. As the angle of attack is increased, a point is reached where the boundary layer can no longer remain attached to the upper surface. When the boundary layer separates, it leaves a region of recirculating flow above the upper surface, as illustrated in the flow-visualization photo at right. This is known as the *stall*, or *stalling*. At angles of attack above the stall, lift is significantly reduced, though it is not zero. The maximum lift that can be achieved before stall, in terms of the lift coefficient, is generally less than 2.0 for single-element airfoils and can be more than 3.0 for airfoils with high-lift slotted flaps deployed.[59]

Bluff bodies[edit]

Further information: Vortex shedding and Vortex-induced vibration

The flow around bluff bodies – i.e. without a streamlined shape, or stalling airfoils – may also generate lift, besides a strong drag force. This lift may be steady, or it may oscillate due to vortex shedding. Interaction of the object's flexibility with the vortex shedding may enhance the effects of fluctuating lift and cause vortex-induced vibrations.[60] For instance, the flow around a circular cylinder generates a Kármán vortex street: vortices being shed in an alternating fashion from each side of the cylinder. The oscillatory nature of the flow is reflected in the fluctuating lift force on the cylinder, whereas the mean lift force is negligible. The lift force frequency is characterised by the dimensionless Strouhal number, which depends (among others) on the Reynolds number of the flow.[61][62]

For a flexible structure, this oscillatory lift force may induce vortex-induced vibrations. Under certain conditions – for instance resonance or strong spanwise correlation of the lift force – the resulting motion of the structure due to the lift fluctuations may be strongly enhanced. Such vibrations may pose problems and threaten collapse in tall man-made structures like industrial chimneys.[60]

In the Magnus effect, a lift force is generated by a spinning cylinder in a freestream. Here the mechanical rotation acts on the boundary layer, causing it to separate at different locations on the two sides of the cylinder. The asymmetric separation changes the effective shape of the cylinder as far as the flow is concerned such that the cylinder acts like a lifting airfoil with circulation in the outer flow.[63]

Mathematical theories of lift[edit]

Mathematical theories of lift are based on continuum fluid mechanics, assuming that air flows as if it were a continuous fluid.[64][65][66] Lift is generated in accordance with the fundamental principles of physics, the most relevant being the following three principles:[67]

- Conservation of momentum, which is a consequence of Newton's laws of motion, especially Newton's second law which relates the net force on an element of air to its rate of momentum change,
- Conservation of Mass, including the assumption that the airfoil's surface is impermeable for the air flowing around, and
- Conservation of energy, which says that energy is neither created nor destroyed.

Because an airfoil affects the flow in a wide area around it, the conservation laws of mechanics are embodied in the form of partial-differential equations combined with a set of boundary condition requirements which the flow has to satisfy at the airfoil surface and far away from the airfoil.[68]

To predict lift requires solving the equations for a particular airfoil shape and flow condition, which generally requires calculations that are so voluminous that they are practical only on a computer, through the methods of Computational Fluid Dynamics (CFD). Determining the net aerodynamic force from a CFD solution requires "adding up" (integrating) the forces due to pressure and shear determined by the CFD over every surface element of the airfoil as described under "Pressure integration".

The Navier-Stokes equations (NS) provide the potentially most accurate theory of lift, but in practice, capturing the effects of turbulence in the boundary layer on the airfoil surface requires sacrificing some accuracy and using the Reynolds-Averaged Navier-Stokes equations (RANS). Simpler but less accurate theories have also been developed.

Navier-Stokes (NS) equations[edit]

These equations represent conservation of mass, Newton's second law (conservation of momentum), conservation of energy, the Newtonian law for the action of viscosity, the Fourier heat conduction law, an equation of state relating density, temperature, and pressure, and formulas for the viscosity and thermal conductivity of the fluid.[69] [70]

In principle, the NS equations, combined with boundary conditions of no through-flow and no slip at the airfoil surface, could be used to predict lift in any situation in ordinary atmospheric flight with high accuracy. However, lifting flows in practical situations always involve turbulence in the boundary layer next to the airfoil surface, at least over the aft portion of the airfoil. Predicting lift by solving the NS equations in their raw form would require the calculations to resolve the details of the turbulence, down to the smallest eddy. This is not yet possible, even on the most powerful current computer.[71] So in principle the NS equations provide a complete and very accurate theory of lift, but practical prediction of lift requires that the effects of turbulence be modeled in the RANS equations rather than computed directly.

Reynolds-Averaged Navier-Stokes (RANS) equations[edit]

These are the NS equations with the turbulence motions averaged over time, and the effects of the turbulence on the time-averaged flow represented by turbulence modeling (an additional set of equations based on a combination of dimensional analysis and empirical information on how turbulence affects a boundary layer in a time-averaged average sense).[72][73] A RANS solution consists of the time-averaged velocity vector, pressure, density, and temperature defined at a dense grid of points surrounding the airfoil.

The amount of computation required is a minuscule fraction (billionths)[71] of what would be required to resolve all of the turbulence motions in a raw NS calculation, and with large computers available it is now practical to carry out RANS calculations for complete airplanes in three dimensions. Because turbulence models are not perfect, the accuracy of RANS calculations is imperfect, but it is good enough to be very helpful to airplane designers. Lift predicted by RANS is usually within a few percent of the actual lift.

Inviscid-flow equations (Euler or potential)[edit]

The Euler equations are the NS equations without the viscosity, heat conduction, and turbulence effects.[74] As with a RANS solution, an Euler solution consists of the velocity vector, pressure, density, and temperature defined at a dense grid of points surrounding the airfoil. While the Euler equations are simpler than the NS equations, they still do not lend themselves to exact analytic solutions.

Further simplification is available through potential flow theory, which reduces the number of unknowns that must be solved for and makes analytic solutions possible in some cases, as described below.

Either Euler or potential-flow calculations predict the pressure distribution on the airfoil surfaces roughly correctly for angles of attack below stall, where they might miss the total lift by as much as 10-20%. At angles of attack above stall, inviscid calculations do not predict that stall has happened, and as a result they grossly overestimate the lift.

In potential-flow theory, the flow is assumed to be irrotational, i.e. that small fluid parcels have no net rate of rotation. Mathematically, this is expressed by the statement that the curlof the velocity vector field is everywhere equal to zero. Irrotational flows have the convenient property that the velocity can be expressed as the gradient of a scalar function called a potential. A flow represented in this way is called potential flow.[75][76][77][78]

In potential-flow theory, the flow is usually further assumed to be incompressible. Incompressible potential-flow theory has the advantage that the equation (Laplace's equation) to be solved for the potential is linear, which allows solutions to be constructed by superposition of other known solutions. The incompressible-potential-flow equation can also be solved by conformal mapping, a method based on the theory of functions of a complex variable. In the early 20th century, before computers were available, conformal mapping was used to generate solutions to the incompressible potential-flow equation for a class of idealized airfoil shapes, providing some of the first practical theoretical predictions of the pressure distribution on a lifting airfoil.

A solution of the potential equation directly determines only the velocity field. The pressure field is deduced from the velocity field through Bernoulli's equation.

Comparison of a non-lifting flow pattern around an airfoil and a lifting flow pattern consistent with the Kutta condition, in which the flow leaves the trailing edge smoothly.

Applying potential-flow theory to a lifting flow requires special treatment and an additional assumption. The problem arises because lift on an airfoil in inviscid flow requires circulation in the flow around the airfoil (See "Circulation and the Kutta-Joukowski theorem" below), but a single potential function that is continuous throughout the domain around the airfoil cannot represent a flow with nonzero circulation. The solution to this problem is to introduce a branch cut, a curve or line from some point on the airfoil surface out to infinite distance, and to allow a jump in the value of the potential across the cut. The jump in the potential imposes circulation in the flow equal to the potential jump and thus allows nonzero circulation to be represented. However, the potential jump is a free parameter that is not determined by the potential equation or the other boundary conditions, and the solution is thus indeterminate. A potential-flow solution exists for any value of the circulation and any value of the lift. One way to resolve this indeterminacy is to impose the Kutta condition,[79][80] which is that, of all the possible solutions, the physically reasonable solution is the one in which the flow leaves the trailing edge smoothly. The streamline sketches illustrate one flow pattern with zero lift, in which the flow goes around the trailing edge and leaves the upper surface ahead of the trailing edge, and another flow pattern with positive lift, in which the flow leaves smoothly at the trailing edge in accordance with the Kutta condition.

Linearized potential flow[edit]

This is potential-flow theory with the further assumptions that the airfoil is very thin and the angle of attack is small.[81] The linearized theory predicts the general character of the airfoil pressure distribution and how it is influenced by airfoil shape and angle of attack, but is not accurate enough for design work. For a 2D airfoil, such calculations can be done in a fraction of a second in a spreadsheet on a PC.

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Circulation and Kutta-Joukowski[edit]

Circulation component of the flow around a moving airfoil.

When an airfoil generates lift, several components of the overall velocity field contribute to a net circulation of air around it: the upward flow ahead of the airfoil, the accelerated flow above, the decelerated flow below, and the downward flow behind.

The circulation can be understood as the total amount of "spinning" (or vorticity) of air around the airfoil.

The Kutta–Joukowski theorem relates the lift on an airfoil to this circulation component of the flow.[49][82][83] In particular, it requires the Kutta condition to be met, in which the rear stagnation point moves to the airfoil trailing edge and attaches there for the duration of flight.

The Kutta-Joukowski theorem is a key element in an explanation of lift that follows the development of the flow around an airfoil as the airfoil starts its motion from rest and a starting vortex is formed and left behind, leading to the formation of circulation around the airfoil.[84][85][86] Lift is then inferred from the Kutta-Joukowski theorem. This explanation is largely mathematical, and its general progression is based on logical inference, not physical cause-and-effect.[87]

The Kutta-Joukowski model does not predict how much circulation or lift a given airfoil will produce. Calculating the lift from Kutta-Joukowski requires a known value for the circulation.

The circulation around a conventional airfoil, and hence the lift it generates, is dictated by both its design and the flight conditions, such as forward velocity and angle of attack. Lift can be increased by artificially increasing the circulation, for example by boundary-layer blowing or the use of blown flaps. In the Flettner rotor the entire airfoil is circular and spins about a spanwise axis to create the circulation.

Lift coefficient[edit]

Main article: lift coefficient

Lift depends on the size of the wing, being approximately proportional to the wing area. It is often convenient to quantify the lift of a given airfoil by its *lift coefficient* , which defines its overall lift in terms of a unit area of the wing.

If the value of for a wing at a specified angle of attack is given, then the lift produced for specific flow conditions can be determined using the following equation:[88]

- is the lift coefficient at the desired angle of attack, Mach number, and Reynolds number[89]

Pressure integration[edit]

When the pressure distribution on the airfoil surface is known, determining the total lift requires adding up the contributions to the pressure force from local elements of the surface, each with its own local value of pressure. The total lift is thus the integral of the pressure, in the direction perpendicular to the farfield flow, over the entire surface of the airfoil or wing.[90]

where: [*clarification needed*]

- **n** is the normal unit vector pointing into the wing, and
- **k** is the vertical unit vector, normal to the freestream direction.

The above lift equation neglects the skin friction forces, which typically have a negligible contribution to the lift compared to the pressure forces.

By using the streamwise vector **i** parallel to the freestream in place of **k** in the integral, we obtain an expression for the pressure drag D_p (which includes the pressure portion of the profile drag and, if the wing is three-dimensional, the induced drag). If we use the spanwise vector **j**, we obtain the side force *Y*.

The validity of this integration generally requires the airfoil shape to be a closed curve that is piecewise smooth.

Control volumes[edit]

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Control volumes of different shapes that have been used in analyzing the momentum balance in the 2D flow around a lifting airfoil. The airfoil is assumed to exert a downward force -L' per unit span on the air, and the proportions in which that force is manifested as momentum fluxes and pressure differences at the outer boundary are indicated for each different shape of control volume

The flow around a lifting airfoil must satisfy Newton's second law, or conservation of momentum, both locally at every point in the flow field, and in an integrated sense over any extended region of the flow. For an extended region, Newton's second law takes the form of the *momentum theorem for a control volume*, where a control volume can be any region of the flow chosen for analysis. The momentum theorem states that the integrated force exerted at the boundaries of the control volume (a surface integral), is equal to the integrated time rate of change (material derivative) of the momentum of fluid parcels passing through the interior of the control volume (a volume integral).[*not in citation given* (*See discussion.*)] For a steady flow, the volume integral can be replaced by the net surface integral of the flux of momentum through the boundary via Stokes' theorem.[91]

The lifting flow around a 2D airfoil is usually analyzed in a control volume that completely surrounds the airfoil, so that the inner boundary of the control volume

is the airfoil surface, where the downward force per unit span is exerted on the fluid by the airfoil. The outer boundary is usually either a large circle or a large rectangle. At this outer boundary distant from the airfoil, the velocity and pressure are well represented by the velocity and pressure associated with a uniform flow plus a vortex, and viscous stress is negligible, so that the only force that must be integrated over the outer boundary is the pressure.[92][93][94] The free-stream velocity is usually assumed to be horizontal, with lift vertically upward, so that the vertical momentum is the component of interest.

For the free-air case (no ground plane), it is found that the force exerted by the airfoil on the fluid is manifested partly as momentum fluxes and partly as pressure differences at the outer boundary, in proportions that depend on the shape of the outer boundary, as shown in the diagram at right. For a flat horizontal rectangle that is much longer than it is tall, the fluxes of vertical momentum through the

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front and back are negligible, and the lift is accounted for entirely by the integrated pressure differences on the top and bottom.[92] For a square or circle, the momentum fluxes and pressure differences account for half the lift each.[92][93][94] For a vertical rectangle that is much taller than it is wide, the unbalanced pressure forces on the top and bottom are negligible, and lift is accounted for entirely by momentum fluxes, with a flux of upward momentum that enters the control volume through the front accounting for half the lift, and a flux of downward momentum that exits the control volume through the back accounting for the other half.[92]

The results of all of the control-volume analyses described above are consistent with the Kutta-Joukowski theorem described above. Both the tall rectangle and circle control volumes have been used in derivations of the theorem.[93][94]

Three-dimensional flow[edit]

Cross-section of an airplane wing-body combination showing the isobars of the three-dimensional lifting flow.

Cross-section of an airplane wing-body combination showing velocity vectors of the three-dimensional lifting flow.

The flow around a real three-dimensional wing involves significant additional issues, especially relating to the wing tips. For a wing of low aspect ratio, such as a typical delta wing, two-dimensional thories may provide a poor model and three-dimensional flow effects can dominate.[95] Even for wings of high aspect ratio, the three-dimensional effects associated with finite span can affect the whole span, not just close to the tips.

Wing tips and spanwise distribution[edit]

The vertical pressure gradient at the wing tips causes air to flow sideways, out from under the wing then up and back over the upper surface. This reduces the pressure gradient at the wing tip, therefore also reducing lift. The lift tends to decrease in the spanwise direction from root to tip, and the pressure distributions around the airfoil sections change accordingly in the spanwise direction. Pressure distributions in planes perpendicular to the flight direction tend to look like the illustration at right.[96] This spanwise-varying pressure distribution is sustained by a mutual interaction with the velocity field. Flow below the wing is accelerated outboard, flow outboard of the tips is accelerated upward, and flow above the wing is accelerated inboard, which results in the flow pattern illustrated at right.[97]

There is more downward turning of the flow than there would be in a two-dimensional flow with the same airfoil shape and sectional lift, and a higher sectional angle of attack is required to achieve the same lift compared to a two-dimensional flow.[98]The wing is effectively flying in a downdraft of its own making, as if the freestream flow were tilted downward, with the result that the total aerodynamic force vector is tilted backward slightly compared to what it would be in two dimensions. The additional backward component of the force vector is called lift-induced drag.

Euler computation of a tip vortex rolling up from the trailed vorticity sheet.

The difference in the spanwise component of velocity above and below the wing (between being in the inboard direction above and in the outboard direction below) persists at the trailing edge and into the wake downstream. After the flow leaves the trailing edge, this difference in velocity takes place across a relatively thin shear layer called a vortex sheet.

Horseshoe vortex system[edit]

Planview of a wing showing the horseshoe vortex system.

The wing tip flow passing behind the wing creates a tip vortex. As the main vortex sheet passes downstream from the trailing edge, it rolls up at its outer edges, merging with the tip vortices. The combination of the wingtip vortices and the vortex sheets feeding them is called the vortex wake.

In addition to the vorticity in the trailing vortex wake there is vorticity in the wing's boundary layer, which is often called the bound vorticity and which connects the trailing sheets from the two sides of the wing into a vortex system in the general form of a horseshoe. The horseshoe form of the vortex system was recognized by the British aeronautical pioneer Blanchester in 1907.[99]

Given the distribution of bound vorticity and the vorticity in the wake, the Biot-Savart law (a vector-calculus relation) can be used to calculate the velocity perturbation anywhere in the field, caused by the lift on the wing. Approximate theories for the lift distribution and lift-induced drag of three-dimensional wings are based on such analysis applied to the wing's horseshoe vortex system.[100][101] In these theories, the bound vorticity is usually idealized and assumed to reside at the camber surface inside the wing.

Because the velocity is deduced from the vorticity in such theories, there is a tendency for some authors to describe the situation in terms that imply that the vorticity is the cause of the velocity perturbations, using terms such as "the velocity induced by the vortex," for example.[102] But attributing causation to the vorticity in this way is not consistent with the physics. The real cause of the velocity perturbations is the pressure field.[103][104][105][*clarification needed*]

Alternative explanations, misconceptions, and controversies[edit]

Many other alternative explanations for the generation of lift by an airfoil have been put forward, a few of which are presented here. Most of them are intended to explain the phenomenon of lift to a general audience. Although the explanations may share features in common with the explanations above, additional assumptions and simplifications may be introduced. This can reduce the validity of an alternative explanation to a limited sub-class of lift generating conditions, or might not allow a quantitative analysis. Several theories introduce assumptions which proved to be wrong, like the *equal transit-time* theory.

False explanation based on equal transit-time[edit]

An illustration of the incorrect equal transit-time explanation of airfoil lift.

Basic or popular sources often describe the "equal transit-time" theory of lift, which incorrectly assumes that the parcels of air that divide at the leading edge of an airfoil must rejoin at the trailing edge, forcing the air traveling along the longer upper surface to go faster. Bernoulli's Principle is then cited to conclude that since the air moves slower along the bottom of the wing, the air pressure must be higher, pushing the wing up.[106]

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However, there is no physical principle that requires equal transit time and experimental results show that this assumption is false.[107][108][109][110][111][112] In fact, the air moving over the top of an airfoil generating lift moves *much faster*than the equal transit theory predicts.[113] Further, the theory violates Newton's third law of motion, since it describes a force on the wing with no opposite force.[114]

The assertion that the air must arrive simultaneously at the trailing edge is sometimes referred to as the "Equal Transit-Time Fallacy".[115][116][117][118][119]

Controversy regarding the Coandă effect[edit]

Main article: Coandă effect

In its original sense, the *Coandă effect* refers to the tendency of a fluid jet to stay attached to an adjacent surface that curves away from the flow, and the resultant entrainment of ambient air into the flow. The effect is named for Henri Coandă, the Romanian aerodynamicist who exploited it in many of his patents.

More broadly, some consider the effect to include the tendency of any fluid boundary layer to adhere to a curved surface, not just the boundary layer accompanying a fluid jet. It is in this broader sense that the Coandă effect is used by some to explain why the air flow remains attached to the top side of an airfoil.[120] Jef Raskin,[121] for example, describes a simple demonstration, using a straw to blow over the upper surface of a wing. The wing deflects upwards, thus demonstrating that the Coandă effect creates lift. This demonstration correctly demonstrates the Coandă effect as a fluid jet (the exhaust from a straw) adhering to a curved surface (the wing). However, the upper surface in this flow is a complicated, vortex-laden mixing layer, while on the lower surface the flow is quiescent. The physics of this demonstration are very different from that of the general flow over the wing.[122] The usage in this sense is encountered in some popular references on aerodynamics.[120][121] This is a controversial use of the term "Coanda effect." The more established view in the aerodynamics field is that the Coandă effect is defined in the more limited sense above,[122][123][124] and the flow following the upper surface simply reflects an absence of boundary-layer separation and is not an example of the Coandă effect.[125][126][127][128]

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Trajectory

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For other uses, see Trajectory (disambiguation).

"Flightpath" redirects here. For other uses, see Flightpath (disambiguation).

A **trajectory** or **flight path** is the path that a moving object follows through space as a function of time.[1] The object might be a projectile or a satellite. For example, it can be an orbit—the path of a planet, an asteroid, or a comet as it travels around a central mass. A trajectory can be described mathematically either by the geometry of the path or as the position of the object over time.

In control theory a trajectory is a time-ordered set of states of a dynamical system (see e.g. Poincaré map). In discrete mathematics, a trajectory is a

sequence of values calculated by the iterated application of a mapping to

an element of its source

Physics of trajectories[edit]

A familiar example of a trajectory is the path of a projectile, such as a thrown ball or rock. In a significantly simplified model, the object moves only under the influence of a uniform gravitational force field. This can be a good approximation for a rock that is thrown for short distances, for example at the surface of the moon. In this simple approximation, the trajectory takes the shape of a parabola. Generally when determining trajectories, it may be necessary to account for nonuniform gravitational forces and air resistance (drag and aerodynamics). This is the focus of the discipline of ballistics.

One of the remarkable achievements of Newtonian mechanics was the derivation of the laws of Kepler. In the gravitational field of a point mass or a spherically-symmetrical extended mass (such as the Sun), the trajectory of a moving object is a conic section, usually an ellipse or a hyperbola.[a] This agrees with the observed orbits of planets, comets, and artificial spacecraft to a reasonably good approximation, although if a comet passes close to the Sun, then it is also influenced by other forces such as the solar wind and radiation pressure, which modify the orbit and cause the comet to eject material into space.

Newton's theory later developed into the branch of theoretical physics known as classical mechanics. It employs the mathematics of differential calculus (which was also initiated by Newton in his youth). Over the centuries, countless scientists have contributed to the development of these two disciplines. Classical mechanics became a most prominent demonstration of the power of rational thought, i.e. reason, in science as well as technology. It helps to understand and predict an enormous range of phenomena; trajectories are but one example.

Consider a particle of mass , moving in a potential field . Physically speaking, mass represents inertia, and the field represents external forces of a particular kind known as "conservative". Given at every relevant position, there is a way to infer the associated force that would act at that position, say from gravity. Not all forces can be expressed in this way, however.

The motion of the particle is described by the second-order differential equation

On the right-hand side, the force is given in terms of , the gradient of the potential, taken at positions along the trajectory. This is the mathematical form of Newton's second law of motion: force equals mass times acceleration, for such situations.

Examples[edit]

Uniform gravity, neither drag nor wind[edit]

Trajectories of a mass thrown at an angle of 70°:

- without drag
- with Stokes drag
- with Newton drag

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The ideal case of motion of a projectile in a uniform gravitational field in the absence of other forces (such as air drag) was first investigated by Galileo Galilei. To neglect the action of the atmosphere in shaping a trajectory would have been considered a futile hypothesis by practical-minded investigators all through the Middle Ages in Europe. Nevertheless, by anticipating the existence of the vacuum, later to be demonstrated on Earth by his collaborator Evangelista Torricelli[citation needed], Galileo was able to initiate the future science

Orbiting objects[edit]

If instead of a uniform downwards gravitational force we consider two bodies orbiting with the mutual gravitation between them, we obtain Kepler's laws of planetary motion. The derivation of these was one of the major works of Isaac Newton and provided much of the motivation for the development of differential calculus.

Catching balls[edit]

If a projectile, such as a baseball or cricket ball, travels in a parabolic path, with negligible air resistance, and if a player is positioned so as to catch it as it descends, he sees its angle of elevation increasing continuously throughout its flight. The tangent of the angle of elevation is proportional to the time since the ball was sent into the air, usually by being struck with a bat. Even when the ball is really descending, near the end of its flight, its angle of elevation seen by the player continues to increase. The player therefore sees it as if it were ascending vertically at constant speed. Finding the place from which the ball appears to rise steadily helps the player to position himself correctly to make the catch. If he is too close to the batsman who has hit the ball, it will appear to rise at an accelerating rate. If he is too far from the batsman, it will appear to slow rapidly, and then to descend.

For a proof of the above statement, see Trajectory of a projectile § Catching balls.

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Atmospheric entry

From Wikipedia, the free encyclopedia

(Redirected from Atmospheric reentry)

"Reentry" redirects here. For other uses, see Reentry (disambiguation).

Mars Exploration Rover (MER) aeroshell, artistic rendition

Atmospheric entry is the movement of an object from outer space into and through the gases of an atmosphere of a planet, dwarf planet or natural satellite. There are two main types of atmospheric entry: uncontrolled entry, such as the entry of astronomical objects, space debris or bolides; and controlled entry (or reentry) of a spacecraft capable of being navigated or following a predetermined course. Technologies and procedures allowing the controlled atmospheric **e**ntry, **d**escent and **l**anding of spacecraft are collectively abbreviated as **EDL**.

Animated illustration of different phases as a meteoroid enters the Earth's atmosphere to become visible as a meteor and land as a meteorite

Atmospheric drag and aerodynamic heating can cause atmospheric breakup capable of completely disintegrating smaller objects. These forces may cause objects with lower compressive strength to explode.

Manned space vehicles must be slowed to subsonic speeds before parachutes or air brakes may be deployed. Such vehicles have kinetic energies typically between 50 and 1800 megajoules, and atmospheric dissipation is the only way of expending the kinetic energy. The amount of rocket fuel required to slow the vehicle would be nearly equal to the amount used to accelerate it initially, and it is thus highly impractical to use retro rockets for the entire Earth re-entry procedure. While the high temperature generated at the surface of the heat shield is due to adiabatic compression, the vehicle's kinetic energy is ultimately lost to gas friction (viscosity) after the vehicle has passed by. Other smaller energy losses include black body radiation directly from the hot gases and chemical reactions between ionized gases.

Ballistic warheads and expendable vehicles do not require slowing at re-entry, and in fact, are made streamlined so as to maintain their speed.

For Earth, atmospheric entry occurs below the Kármán line at an altitude of more than 100 km (62 mi) above the surface, while at Venus atmospheric entry occurs at 250 km (155 mi) and at Mars atmospheric entry at about 80 km (50 mi). Uncontrolled, objects accelerate through the atmosphere at extreme velocities under the influence of Earth's gravity. Most controlled objects enter at hypersonic speeds due to their suborbital (e.g., intercontinental ballistic missile reentry vehicles), orbital (e.g., the Space Shuttle), or unbounded (e.g., meteors) trajectories. Various advanced technologies have been developed to enable atmospheric reentry and flight at extreme velocities. An alternative low velocity method of controlled atmospheric entry is buoyancy[1] which is suitable for planetary entry where thick atmospheres, strong gravity or both factors complicate high-velocity hyperbolic entry, such as the atmospheres of Venus, Titan and the gas giants.[2]

History[edit]

Apollo Command Module flying at a high angle of attack for lifting entry, artistic rendition.

The concept of the ablative heat shield was described as early as 1920 by Robert Goddard: "In the case of meteors, which enter the atmosphere with speeds as high as 30 miles per second (48 km/s), the interior of the meteors remains cold, and the erosion is due, to a large extent, to chipping or cracking of the suddenly heated surface. For this reason, if the outer surface of the apparatus were to consist of layers of a very infusible hard substance with layers of a poor heat conductor between, the surface would not be eroded to any considerable extent, especially as the velocity of the apparatus would not be nearly so great as that of the average meteor."[3]

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Practical development of reentry systems began as the range and reentry velocity of ballistic missiles increased. For early short-range missiles, like the V-2, stabilization and aerodynamic stress were important issues (many V-2s broke apart during reentry), but heating was not a serious problem. Medium-range missiles like the Soviet R-5, with a 1200 km range, required ceramic composite heat shielding on separable reentry vehicles (it was no longer possible for the entire rocket structure to survive re-entry). The first ICBMs, with ranges of 8000 to 12,000 km, were only possible with the development of modern ablative heat shields and blunt-shaped vehicles. In the U.S., this technology was pioneered by H. Julian Allen at Ames Research Center.[4]

Terminology, definitions and jargon[edit]

Over the decades since the 1950s, a rich technical jargon has grown around the engineering of vehicles designed to enter planetary atmospheres. It is recommended that the reader review the jargon glossary before continuing with this article on atmospheric reentry.

When atmospheric entry is part of a spacecraft landing or recovery, particularly on a planetary body other than Earth, entry is part of a phase referred to as "entry, descent, and landing", or EDL.[5] When the atmospheric entry returns to the same body that the vehicle had launched from, the event is referred to as **reentry** (almost always referring to Earth entry).

Blunt body entry vehicles[edit]

Various reentry shapes (NASA) using shadowgraphs to show high-velocity flow

These four shadowgraph images represent early reentry-vehicle concepts. A shadowgraph is a process that makes visible the disturbances that occur in a fluid flow at high velocity, in which light passing through a flowing fluid is refracted by the density gradients in the fluid resulting in bright and dark areas on a screen placed behind the fluid.

In the United States, H. Julian Allen and A. J. Eggers, Jr. of the National Advisory Committee for Aeronautics (NACA) made the counterintuitive discovery in 1951[6] that a blunt shape (high drag) made the most effective heat shield. From simple engineering principles, Allen and Eggers showed that the heat load experienced by an entry vehicle was inversely proportional to the drag coefficient, i.e. the greater the drag, the less the heat load. If the reentry vehicle is made blunt, air cannot "get out of the way" quickly enough, and acts as an air cushion to push the shock wave and heated shock layer forward (away from the vehicle). Since most of the hot gases are no longer in direct contact with the vehicle, the heat energy would stay in the shocked gas and simply move around the vehicle to later dissipate into the atmosphere.

The Allen and Eggers discovery, though initially treated as a military secret, was eventually published in 1958.[7]

Entry vehicle shapes[edit]

Main article: Nose cone design

There are several basic shapes used in designing entry vehicles:

Sphere or spherical section[edit]

The simplest axisymmetric shape is the sphere or spherical section.[8] This can either be a complete sphere or a spherical section forebody with a converging conical afterbody. The aerodynamics of a sphere or spherical section are easy to model analytically using Newtonian impact theory. Likewise, the spherical section's heat flux can be accurately modeled with the Fay-Riddell equation.[9] The static stability of a spherical section is assured if the vehicle's center of mass is upstream from the center of curvature (dynamic stability is more problematic). Pure spheres have no lift. However, by flying at an angle of attack, a spherical section has modest aerodynamic lift thus providing some cross-range capability and widening its entry corridor. In the late 1950s and early 1960s, high-speed computers were not yet available and computational fluid dynamics was still embryonic. Because the spherical section was amenable to closed-form analysis, that geometry became the default for conservative design. Consequently, manned capsules of that era were based upon the spherical section.

Pure spherical entry vehicles were used in the early Soviet Vostok and Voskhod and in Soviet Mars and Venera descent vehicles.

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The Apollo Command/Service Module used a spherical section forebody heat shield with a converging conical afterbody. It flew a lifting entry with a hypersonic trim angle of attack of −27° (0° is blunt-end first) to yield an average L/D (lift-to-drag ratio) of 0.368.[10] This angle of attack was achieved by precisely offsetting the vehicle's center of mass from its axis of symmetry. Other examples of the spherical section geometry in manned capsules are Soyuz/Zond, Gemini and Mercury. Even these small amounts of lift allow trajectories that have very significant effects on peak g-force (reducing g-force from 8-9g for a purely ballistic (slowed only by drag) trajectory to 4-5g) as well as greatly reducing the peak reentry heat.[11]

Sphere-cone[edit]

The sphere-cone is a spherical section with a frustum or blunted cone attached. The sphere-cone's dynamic stability is typically better than that of a spherical section. The vehicle enters sphere-first. With a sufficiently small half-angle and properly placed center of mass, a sphere-cone can provide aerodynamic stability from Keplerian entry to surface impact. (The "half-angle" is the angle between the cone's axis of rotational symmetry and its outer surface, and thus half the angle made by the cone's surface edges.)

Prototype of the Mk-2 Reentry Vehicle (RV), based on blunt body theory

The original American sphere-cone aeroshell was the Mk-2 RV (reentry vehicle), which was developed in 1955 by the General Electric Corp.The Mk-2's design was derived from blunt-body theory and used a radiatively cooled thermal protection system (TPS) based upon a metallic heat shield (the different TPS types are later described in this article). The Mk-2 had significant defects as a weapon delivery system, i.e., it loitered too long in the upper atmosphere due to its lower ballistic coefficient and also trailed a stream of vaporized metal making it very visible to radar. These defects made the Mk-2 overly susceptible to anti-ballistic missile (ABM) systems. Consequently, an alternative sphere-cone RV to the Mk-2 was developed by General Electric.[*citation needed*]

Mk-6 RV, Cold War weapon and ancestor to most of the U.S. missile entry vehicles

This new RV was the Mk-6 which used a non-metallic ablative TPS (nylon phenolic). This new TPS was so effective as a reentry heat shield that significantly reduced bluntness was possible.[citation needed] However, the Mk-6 was a huge RV with an entry mass of 3360 kg, a length of 3.1 meters and a half-angle of 12.5°. Subsequent advances in nuclear weapon and ablative TPS design allowed RVs to become significantly smaller with a further reduced bluntness ratio compared to the Mk-6. Since the 1960s, the sphere-cone has become the preferred geometry for modern ICBM RVs with typical half-angles being between 10° to 11°.[citation needed]

"Discoverer" type reconnaissance satellite film Recovery Vehicle (RV)

Reconnaissance satellite RVs (recovery vehicles) also used a sphere-cone shape and were the first American example of a non-munition entry vehicle (Discoverer-I, launched on 28 February 1959). The sphere-cone was later used for space exploration missions to other celestial bodies or for return from open space; e.g., Stardust probe. Unlike with military RVs, the advantage of the blunt body's lower TPS mass remained with space exploration entry vehicles like the Galileo Probe with a half angle of 45° or the Viking aeroshell with a half angle of 70°. Space exploration sphere-cone entry vehicles have landed on the surface or entered the atmospheres of Mars, Venus, Jupiter and Titan.

Galileo Probe during final assembly

Biconic[edit]

The biconic is a sphere-cone with an additional frustum attached. The biconic offers a significantly improved L/D ratio. A biconic designed for Mars aerocapture typically has an L/D of approximately 1.0 compared to an L/D of 0.368 for the Apollo-CM. The higher L/D makes a biconic shape better suited for transporting people to Mars due to the lower peak deceleration. Arguably, the most significant biconic ever flown was the *Advanced Maneuverable Reentry Vehicle* (AMaRV). Four AMaRVs were made by the McDonnell-Douglas Corp. and represented a significant leap in RV sophistication. Three AMaRVs were launched by Minuteman-1 ICBMs on 20 December 1979, 8 October 1980 and 4 October 1981. AMaRV had an entry mass of approximately 470 kg, a nose radius of 2.34 cm, a forward frustum half-angle of 10.4°, an inter-frustum radius of 14.6 cm, aft frustum half angle of 6°, and an axial length of 2.079 meters. No accurate diagram or picture of AMaRV has ever appeared in the open literature. However, a schematic sketch of an AMaRV-like vehicle along with trajectory plots showing hairpin turns has been published.[12]The DC-X, shown during its first flight, was a prototype single stage to orbit vehicle, and used a biconic shape similar to AMaRV.

Opportunity rover's heat shield lying inverted on the surface of Mars.

AMaRV's attitude was controlled through a split body flap (also called a "split-windward flap") along with two yaw flaps mounted on the vehicle's sides. Hydraulic actuation was used for controlling the flaps. AMaRV was guided by a fully autonomous navigation system designed for evading anti-ballistic missile (ABM) interception. The McDonnell Douglas DC-X (also a biconic) was essentially a scaled-up version of AMaRV. AMaRV and the DC-X also served as the basis for an unsuccessful proposal for what eventually became the Lockheed Martin X-33.

Non-axisymmetric shapes[edit]

Non-axisymmetric shapes have been used for manned entry vehicles. One example is the winged orbit vehicle that uses a delta wing for maneuvering during descent much like a conventional glider. This approach has been used by the American Space Shuttleand the Soviet Buran. The lifting body is another entry vehicle geometry and was used with the X-23 PRIME (Precision Recovery Including Maneuvering Entry) vehicle.[*citation needed*]

The FIRST (Fabrication of Inflatable Re-entry Structures for Test) system was an Aerojet proposal for an inflated-spar Rogallo wing made up from Inconel wire cloth impregnated with silicone rubber and silicon carbide dust. FIRST was proposed in both one-man and six man versions, used for emergency escape and reentry of stranded space station crews, and was based on an earlier unmanned test program that resulted in a partially successful reentry flight from space (the launcher nose cone fairing hung up on the material, dragging it too low and fast for the thermal protection system (TPS), but otherwise it appears the concept would have worked; even with the fairing dragging it, the test article flew stably on reentry until burn-through).[citation needed]

The proposed MOOSE system would have used a one-man inflatable ballistic capsule as an emergency astronaut entry vehicle. This concept was carried further by the Douglas Paracone project. While these concepts were unusual, the inflated shape on reentry was in fact axisymmetric.[citation needed]

Shock layer gas physics[edit]

At typical reentry temperatures, the air in the shock layer is both ionized and dissociated.[citation needed] This chemical dissociation necessitates various physical models to describe the shock layer's thermal and chemical properties. There are four basic physical models of a gas that are important to aeronautical engineers who design heat shields:

Perfect gas model[edit]

Almost all aeronautical engineers are taught the perfect (ideal) gas model during their undergraduate education. Most of the important perfect gas equations along with their corresponding tables and graphs are shown in NACA Report 1135.[13] Excerpts from NACA Report 1135 often appear in the appendices of thermodynamics textbooks and are familiar to most aeronautical engineers who design supersonic aircraft.

The perfect gas theory is elegant and extremely useful for designing aircraft but assumes that the gas is chemically inert. From the standpoint of aircraft design, air can be assumed to be inert for temperatures less than 550 K at one atmosphere pressure. The perfect gas theory begins to break down at 550 K and is not usable at temperatures greater than 2,000 K. For temperatures greater than 2,000 K, a heat shield designer must use a *real gas model*.

Real (equilibrium) gas model[edit]

An entry vehicle's pitching moment can be significantly influenced by real-gas effects. Both the Apollo-CM and the Space Shuttle were designed using incorrect pitching moments determined through inaccurate real-gas modelling. The Apollo-

CM's trim-angle angle of attack was higher than originally estimated, resulting in a narrower lunar return entry corridor. The actual aerodynamic centre of the *Columbia* was upstream from the calculated value due to real-gas effects. On *Columbia*'s maiden flight (STS-1), astronauts John W. Young and Robert Crippen had some anxious moments during reentry when there was concern about losing control of the vehicle.[14]

An equilibrium real-gas model assumes that a gas is chemically reactive, but also assumes all chemical reactions have had time to complete and all components of the gas have the same temperature (this is called *thermodynamic equilibrium*). When air is processed by a shock wave, it is superheated by compression and chemically dissociates through many different reactions. Direct friction upon the reentry object is not the main cause of shock-layer heating. It is caused mainly from isentropic heating of the air molecules within the compression wave. Friction based entropy increases of the molecules within the wave also account for some heating.[*original research?*] The distance from the shock wave to the stagnation point on the entry vehicle's leading edge is called *shock wave stand off*. An approximate rule of thumb for shock wave standoff distance is 0.14 times the nose radius. One can estimate the time of travel for a gas molecule from the shock wave to the stagnation point by assuming a free stream velocity of 7.8 km/s and a nose radius of 1 meter, i.e., time of travel is about 18 microseconds. This is roughly the time required for shock-wave-initiated chemical dissociation to approach chemical equilibrium in a shock layer for a 7.8 km/s entry into air during peak heat flux. Consequently, as air approaches the entry vehicle's stagnation point, the air effectively reaches chemical equilibrium thus enabling an equilibrium model to be usable. For this case, most of the shock layer between the shock wave and leading edge of an entry vehicle is chemically reacting and *not* in a state of equilibrium. The Fay-Riddell equation,[9] which is of extreme importance towards modeling heat flux, owes its validity to the stagnation point being in chemical equilibrium. The time required for the shock layer gas to reach equilibrium is strongly dependent upon the shock layer's pressure. For example, in the case of the Galileo Probe's entry into Jupiter's atmosphere, the shock layer was mostly in equilibrium during peak heat flux due to the very high pressures experienced (this is counterintuitive given the free stream velocity was 39 km/s during peak heat flux).

Determining the thermodynamic state of the stagnation point is more difficult under an equilibrium gas model than a perfect gas model. Under a perfect gas model, the *ratio of specific heats* (also called "isentropic exponent", adiabatic index, "gamma" or "kappa") is assumed to be constant along with the gas constant. For a real gas, the ratio of specific heats can wildly oscillate as a function of temperature. Under a perfect gas model there is an elegant set of equations for determining thermodynamic state along a constant entropy stream line called the *isentropic chain*. For a real gas, the isentropic chain is unusable and a *Mollier diagram* would be used instead for manual calculation. However, graphical solution with a Mollier diagram is now considered obsolete with modern heat shield designers using computer programs based upon a digital lookup table (another form of Mollier diagram) or a chemistry based thermodynamics program. The chemical composition of a gas in equilibrium with fixed pressure and temperature can be determined through the *Gibbs free energy method*. Gibbs free energy is simply the total enthalpy of the gas minus its total entropy times temperature. A chemical equilibrium program normally does not require chemical formulas or reaction-rate equations. The program works by preserving the original elemental abundances specified for the gas and varying the different molecular combinations of the elements through numerical iteration until the lowest possible Gibbs free energy is calculated (a Newton-Raphson method is the usual numerical scheme). The data base for a Gibbs free energy program comes from spectroscopic data used in defining partition functions. Among the best equilibrium codes in existence is the program *Chemical Equilibrium with Applications* (CEA) which was written by Bonnie J. McBride and Sanford Gordon at NASA Lewis (now renamed "NASA Glenn Research Center"). Other names for CEA are the "Gordon and McBride Code" and the "Lewis Code". CEA is quite accurate up to 10,000 K for planetary atmospheric gases, but unusable beyond 20,000 K (double ionization is not modelled). CEA can be downloaded from the Internet along with full documentation and will compile on Linux under the G77 Fortran compiler.

Real (non-equilibrium) gas model[edit]

A non-equilibrium real gas model is the most accurate model of a shock layer's gas physics, but is more difficult to solve than an equilibrium model. The simplest non-equilibrium model is the *Lighthill-Freeman model*.[15][16] The Lighthill-Freeman model initially assumes a gas made up of a single diatomic species susceptible to only one chemical formula and its reverse; e.g., $N_2 \rightarrow N + N$ and $N + N \rightarrow N_2$ (dissociation and recombination). Because of its simplicity, the Lighthill-Freeman model is a useful pedagogical tool, but is unfortunately too simple for modelling non-equilibrium air. Air is typically assumed to have a mole fraction composition of 0.7812 molecular nitrogen, 0.2095 molecular oxygen and 0.0093 argon. The simplest real gas model for air is the *five species model*, which is based upon N_2, O_2, NO, N, and O. The five species model assumes no ionization and ignores trace species like carbon dioxide.

When running a Gibbs free energy equilibrium program, the iterative process from the originally specified molecular composition to the final calculated equilibrium composition is essentially random and not time accurate. With a non-equilibrium program, the computation process is time accurate and follows a solution path dictated by chemical and reaction rate formulas. The five species model has 17 chemical formulas (34 when counting reverse formulas). The Lighthill-Freeman model is based upon a single ordinary differential equation and one algebraic equation. The five species model is based upon 5 ordinary differential equations and 17 algebraic equations. Because the 5 ordinary differential equations are loosely coupled, the system is numerically "stiff" and difficult to solve. The five species model is only usable for entry from low Earth orbit where entry velocity is approximately 7.8 km/s. For lunar return entry of 11 km/s, the shock layer contains a significant amount of ionized nitrogen and oxygen. The five species model is no longer accurate and a twelve species model must be used instead. High speed Mars entry which involves a carbon dioxide, nitrogen and argon atmosphere is even more complex requiring a 19 species model.

An important aspect of modelling non-equilibrium real gas effects is radiative heat flux. If a vehicle is entering an atmosphere at very high speed (hyperbolic trajectory, lunar return) and has a large nose radius then radiative heat flux can dominate TPS heating. Radiative heat flux during entry into an air or carbon dioxide atmosphere typically comes from asymmetric diatomic molecules; e.g., cyanogen (CN), carbon monoxide, nitric oxide (NO), single ionized molecular nitrogen etc. These molecules are formed by the shock wave dissociating ambient atmospheric gas followed by recombination within the shock layer into new molecular species. The newly formed diatomic molecules initially have a very high vibrational temperature that efficiently transforms the vibrational energy into radiant energy; i.e., radiative heat flux. The whole process takes place in less than a millisecond which makes modelling a challenge. The experimental measurement of radiative heat flux (typically done with shock tubes) along with theoretical calculation through the unsteady Schrödinger equation are among the more esoteric aspects of aerospace engineering. Most of the aerospace research work related to understanding radiative heat flux was done in the 1960s, but largely discontinued after conclusion of the Apollo Program. Radiative heat flux in air was just sufficiently understood to ensure Apollo's success. However, radiative heat flux in carbon dioxide (Mars entry) is still barely understood and will require major research.

Frozen gas model[edit]

The frozen gas model describes a special case of a gas that is not in equilibrium. The name "frozen gas" can be misleading. A frozen gas is not "frozen" like ice is frozen water. Rather a frozen gas is "frozen" in time (all chemical reactions are assumed to have stopped). Chemical reactions are normally driven by collisions between molecules. If gas pressure is slowly reduced such that chemical reactions can continue then the gas can remain in equilibrium. However, it is possible for gas pressure to be so suddenly reduced that almost all chemical reactions stop. For that situation the gas is considered frozen.

The distinction between equilibrium and frozen is important because it is possible for a gas such as air to have significantly different properties (speed-of-sound, viscosity etc.) for the same thermodynamic state; e.g., pressure and temperature. Frozen gas can be a significant issue in the wake behind an entry vehicle. During reentry, free stream air is compressed to high temperature and pressure by the entry vehicle's shock wave. Non-equilibrium air in the shock layer is then transported past the entry vehicle's leading side into a region of rapidly expanding flow that causes freezing. The frozen air can then be entrained into a trailing vortex behind the entry vehicle. Correctly modelling the flow in the wake of an entry vehicle is very difficult. Thermal protection shield (TPS) heating in the vehicle's afterbody is usually not very high, but the geometry and unsteadiness of the vehicle's wake can significantly influence aerodynamics (pitching moment) and particularly dynamic stability.

Thermal protection systems[edit]

A **thermal protection system** or TPS is the barrier that protects a spacecraft during the searing heat of atmospheric reentry. A secondary goal may be to protect the spacecraft from the heat and cold of space while in orbit. Multiple approaches for the thermal protection of spacecraft are in use, among them ablative heat shields, passive cooling and active cooling of spacecraft surfaces.

Ablative[edit]

Ablative heat shield (after use) on Apollo 12 capsule

The ablative heat shield functions by lifting the hot shock layer gas away from the heat shield's outer wall (creating a cooler boundary layer). The boundary layer comes from *blowing* of gaseous reaction products from the heat shield material and provides protection against all forms of heat flux. The overall process of reducing the heat flux experienced by the heat shield's outer wall by way of a boundary layer is called *blockage*. Ablation occurs at two levels in an ablative TPS: the outer surface of the TPS material chars, melts, and sublimes, while the bulk of the TPS material undergoes pyrolysis and expels product gases. The gas produced by pyrolysis is what drives blowing and causes blockage of convective and catalytic heat flux. Pyrolysis can be measured in real time using thermogravimetric analysis, so that the ablative performance can be evaluated.[17] Ablation can also provide blockage against radiative heat flux by introducing carbon into the shock layer thus making it optically opaque. Radiative heat flux blockage was the primary thermal protection mechanism of the Galileo Probe TPS material (carbon phenolic). Carbon phenolic was originally developed as a rocket nozzle throat material (used in the Space Shuttle Solid Rocket Booster) and for re-entry vehicle nose tips.

Early research on ablation technology in the USA was centered at NASA's Ames Research Center located at Moffett Field, California. Ames Research Center was ideal, since it had numerous wind tunnels capable of generating varying wind velocities. Initial experiments typically mounted a mock-up of the ablative material to be analyzed within a hypersonic wind tunnel.[18] Testing of ablative materials occurs at the Ames Arc Jet Complex. Many spacecraft thermal protection systems have been tested in this facility, including the Apollo, space shuttle, and Orion heat shield materials.[19]

Mars Pathfinder during final assembly showing the aeroshell, cruise ring and solid rocket motor

The thermal conductivity of a particular TPS material is usually proportional to the material's density.[20] Carbon phenolic is a very effective ablative material, but also has high density which is undesirable. If the heat flux experienced by an entry vehicle is insufficient to cause pyrolysis then the TPS material's conductivity could allow heat flux conduction into the TPS bondline material thus leading to TPS failure. Consequently, for entry trajectories causing lower heat flux, carbon phenolic is sometimes inappropriate and lower density TPS materials such as the following examples can be better design choices:

SLA-561V[edit]

SLA in *SLA-561V* stands for *super light-weight ablator*. SLA-561V is a proprietary ablative made by Lockheed Martin that has been used as the primary TPS material on all of the 70° sphere-cone entry vehicles sent by NASA to Mars other than the Mars Science Laboratory (MSL). SLA-561V begins significant ablation at a heat flux of approximately 110 W/cm², but will fail for heat fluxes greater than 300 W/cm². The MSL aeroshell TPS is currently designed to withstand a peak heat flux of 234 W/cm². The peak heat flux experienced by the Viking-1 aeroshell which landed on Mars was 21 W/cm². For Viking-1, the TPS acted as a charred thermal insulator and never experienced significant ablation. Viking-1 was the first Mars lander and based upon a very conservative design. The Viking aeroshell had a base diameter of 3.54 meters (the largest used on Mars until Mars Science Laboratory). SLA-561V is applied by packing the ablative material into a honeycomb core that is pre-bonded to the aeroshell's structure thus enabling construction of a large heat shield.[21]

NASA's Stardust sample return capsule successfully landed at the USAF Utah Range.

Phenolic impregnated carbon ablator[edit]

Phenolic impregnated carbon ablator (PICA), a carbon fiber preform impregnated in phenolic resin,[22] is a modern TPS material and has the advantages of low density (much lighter than carbon phenolic) coupled with efficient ablative ability at high heat flux. It is a good choice for ablative applications such as high-peak-heating conditions found on sample-return missions or lunar-return missions. PICA's thermal conductivity is lower than other high-heat-flux ablative materials, such as conventional carbon phenolics.[*citation needed*]

PICA was patented by NASA Ames Research Center in the 1990s and was the primary TPS material for the Stardust aeroshell.[23] The Stardust sample-return capsule was the fastest man-made object ever to reenter Earth's atmosphere (12.4 km/s (28,000 mph) at 135 km altitude). This was faster than the Apollo mission capsules and 70% faster than the Shuttle.[24] PICA was critical for the viability of the Stardust mission, which returned to Earth in 2006. Stardust's heat shield (0.81 m base diameter) was made of one monolithic piece sized to withstand a nominal peak heating rate of 1.2 kW/cm^2. A PICA heat shield was also used for the Mars Science Laboratory entry into the Martian atmosphere.[25]

PICA-X[edit]

An improved and easier to produce version called PICA-X was developed by SpaceX in 2006-2010[25] for the Dragon space capsule.[26] The first re-entry test of a PICA-X heat shield was on the Dragon C1 mission on 8 December 2010.[27] The PICA-X heat shield was designed, developed and fully qualified by a small team of only a dozen engineers and technicians in less than four years.[25] PICA-X is ten times less expensive to manufacture than the NASA PICA heat shield material.[28]

The Dragon 1 spacecraft initially used PICA-X version 1 and was later equipped with version 2. The Dragon V2 spacecraft uses PICA-X version 3. SpaceX has

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indicated that each new version of PICA-X primarily improves upon heat shielding capacity rather than the manufacturing cost.[*citation needed*]

SIRCA[edit]

Deep Space 2 impactoraeroshell, a classic 45° sphere-cone with spherical section afterbody enabling aerodynamic stability from atmospheric entry to surface impact

Silicone-impregnated reusable ceramic ablator (SIRCA) was also developed at NASA Ames Research Center and was used on the Backshell Interface Plate (BIP) of the Mars Pathfinder and Mars Exploration Rover (MER) aeroshells. The BIP was at the attachment points between the aeroshell's backshell (also called the *afterbody* or *aft cover*) and the *cruise ring* (also called the *cruise stage*). SIRCA was also the primary TPS material for the unsuccessful Deep Space 2 (DS/2) Mars impactor probes with their 0.35 m base diameter aeroshells. SIRCA is a monolithic, insulating material that can provide thermal protection through ablation. It is the only TPS material that can be machined to custom shapes and then applied directly to the spacecraft. There is no post-processing, heat treating, or additional coatings required (unlike Space Shuttle tiles). Since SIRCA can be machined to precise shapes, it can be applied as tiles, leading edge sections, full nose caps, or in any number of custom shapes or sizes. As of 1996, SIRCA had been demonstrated in backshell interface applications, but not yet as a forebody TPS material.[29]

AVCOAT[edit]

AVCOAT is a NASA-specified ablative heat shield, a glass-filled epoxy-novolac system.[30]

NASA originally used it for the Apollo capsule and then utilized the material for its next-generation beyond low Earth-orbit Orion spacecraft.[31] The Avcoat to be used on Orion has been reformulated to meet environmental legislation that has been passed since the end of Apollo.[32][33]

Thermal soak[edit]

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Astronaut Andrew S. W. Thomastakes a close look at TPS tiles underneath Space Shuttle Atlantis.

Rigid black LI-900 tiles were used on the Space Shuttle.

Thermal soak is a part of almost all TPS schemes. For example, an ablative heat shield loses most of its thermal protection effectiveness when the outer wall temperature drops below the minimum necessary for pyrolysis. From that time to the end of the heat pulse, heat from the shock layer convects into the heat shield's outer wall and would eventually conduct to the payload.[citation needed]This outcome is prevented by ejecting the heat shield (with its heat soak) prior to the heat conducting to the inner wall.

Typical Space Shuttle TPS tiles (LI-900) have remarkable thermal protection properties. An LI-900 tile exposed to a temperature of 1000 K on one side will remain merely warm to the touch on the other side. However, they are relatively brittle and break easily, and cannot survive in-flight rain.

Passively cooled[edit]

In some early ballistic missile RVs (e.g., the Mk-2 and the suborbital Mercury spacecraft), *radiatively cooled TPS* were used to initially absorb heat flux during the heat pulse, and, then, after the heat pulse, radiate and convect the stored heat back into the atmosphere. However, the earlier version of this technique required a considerable quantity of metal TPS (e.g., titanium, beryllium, copper, etc.). Modern designers prefer to avoid this added mass by using ablative and thermal-soak TPS instead.

The Mercury capsule design (shown here with its escape tower) originally used a radiatively cooled TPS, but was later converted to an ablative TPS.

Radiatively cooled TPS can still be found on modern entry vehicles, but reinforced carbon-carbon (RCC) (also called *carbon-carbon*) is normally used instead of metal. RCC was the TPS material on the Space Shuttle's nose cone and wing leading edges, and was also proposed as the leading-edge material for the X-33. Carbon is the most refractory material known, with a one-atmosphere sublimation temperature of 3825 °C for graphite. This high temperature made carbon an obvious choice as a radiatively cooled TPS material. Disadvantages of RCC are that it is currently expensive to manufacture, is heavy, and lacks robust impact resistance.[34]

Some high-velocity aircraft, such as the SR-71 Blackbird and Concorde, deal with heating similar to that experienced by spacecraft, but at much lower intensity, and for hours at a time. Studies of the SR-71's titanium skin revealed that the metal structure was restored to its original strength through annealing due to aerodynamic heating. In the case of the Concorde, the aluminium nose was permitted to reach a maximum operating temperature of 127 °C (approximately 180 °C warmer than the, normally sub-zero, ambient air); the metallurgical implications (loss of temper) that would be associated with a higher peak temperature were the most significant factors determining the top speed of the aircraft.

A radiatively cooled TPS for an entry vehicle is often called a *hot-metal TPS*. Early TPS designs for the Space Shuttle called for a hot-metal TPS based upon a nickel superalloy (dubbed René 41) and titanium shingles.[35] This Shuttle TPS concept was rejected, because it was believed a silica-tile-based TPS would involve lower development and manufacturing costs.[*citation needed*] A nickel superalloy-shingle TPS was again proposed for the unsuccessful X-33 single-stage-to-orbit (SSTO) prototype.[36]

Recently, newer radiatively cooled TPS materials have been developed that could be superior to RCC. Known as Ultra-High Temperature Ceramics, they were developed for the prototype vehicle Slender Hypervelocity Aerothermodynamic Research Probe (SHARP). These TPS materials are based on zirconium diboride and hafnium diboride. SHARP TPS have suggested performance improvements allowing for sustained Mach 7 flight at sea level, Mach 11 flight at 100,000 ft (30,000 m) altitudes, and significant improvements for vehicles designed for continuous hypersonic flight. SHARP TPS materials enable sharp leading edges and nose cones to greatly reduce drag for airbreathing combined-cycle-propelled spaceplanes and lifting bodies. SHARP materials have exhibited effective TPS characteristics from zero to more than 2,000 °C, with melting points over 3,500 °C. They are structurally stronger than RCC, and, thus, do not require structural reinforcement with materials such as Inconel. SHARP materials are extremely efficient at reradiating absorbed heat, thus eliminating the need for additional TPS behind and between the SHARP materials and conventional vehicle structure. NASA initially funded (and discontinued) a multi-phase R&D program through the University of Montana in 2001 to test SHARP materials on test vehicles.[37][38]

Actively cooled[edit]

Various advanced reusable spacecraft and hypersonic aircraft designs have been proposed to employ heat shields made from temperature-resistant metal alloys that incorporated a refrigerant or cryogenic fuel circulating through them. Such a TPS concept was proposed for the X-30 National Aerospace Plane (NASP). The NASP was supposed to have been a scramjet powered hypersonic aircraft, but failed in development.

In the early 1960s various TPS systems were proposed to use water or other cooling liquid sprayed into the shock layer, or passed through channels in the heat shield. Advantages included the possibility of more all-metal designs which would be cheaper to develop, be more rugged, and eliminate the need for classified technology. The disadvantages are increased weight and complexity, and lower reliability. The concept has never been flown, but a similar technology (the plug nozzle[39]) did undergo extensive ground testing.

Feathered reentry[edit]

In 2004, aircraft designer Burt Rutan demonstrated the feasibility of a shape-changing airfoil for reentry with the suborbital SpaceShipOne. The wings on this craft rotate upward into the *feather configuration* that provides a shuttlecock effect. Thus SpaceShipOne achieves much more aerodynamic drag on reentry while not experiencing significant thermal loads.

The configuration increases drag, as the craft is now less streamlined and results in more atmospheric gas particles hitting the spacecraft at higher altitudes than otherwise. The aircraft thus slows down more in higher atmospheric layers which is the key to efficient reentry. Secondly, the aircraft will *automatically* orient itself in this state to a high drag attitude.[40]

However, the velocity attained by SpaceShipOne prior to reentry is much lower than that of an orbital spacecraft, and engineers, including Rutan, recognize that a feathered reentry technique is not suitable for return from orbit.

On 4 May 2011, the first test on the SpaceShipTwo of the feathering mechanism was made during a glideflight after release from the White Knight Two.

The feathered reentry was first described by Dean Chapman of NACA in 1958.[41] In the section of his report on *Composite Entry*, Chapman described a solution to the problem using a high-drag device:

It may be desirable to combine lifting and nonlifting entry in order to achieve some advantages... For landing maneuverability it obviously is advantageous to employ a lifting vehicle. The total heat absorbed by a lifting vehicle, however, is much higher than for a nonlifting vehicle... Nonlifting vehicles can more easily be constructed... by employing, for example, a large, light drag device... The larger the device, the smaller is the heating rate.

Nonlifting vehicles with shuttlecock stability are advantageous also from the viewpoint of minimum control requirements during entry.

... an evident composite type of entry, which combines some of the desirable features of lifting and nonlifting trajectories, would be to enter first without lift but with a... drag device; then, when the velocity is reduced to a certain value... the device is jettisoned or retracted, leaving a lifting vehicle... for the remainder of the descent.

Inflatable heat shield reentry[edit]

NASA engineers check IRVE

Deceleration for atmospheric reentry, especially for higher-speed Mars-return missions, benefits from maximizing "the drag area of the entry system. The larger the diameter of the aeroshell, the bigger the payload can be."[42] An inflatable aeroshell provides one alternative for enlarging the drag area with a low-mass design.

Such an inflatable shield/aerobrake was designed for the penetrators of Mars 96 mission. Since the mission failed due to the launcher malfunction, the NPO Lavochkin and DASA/ESA have designed a mission for Earth orbit. The Inflatable Reentry and Descent Technology (IRDT) demonstrator was launched on Soyuz-Fregat on 8 February 2000. The inflatable shield was designed as a cone with two stages of inflation. Although the second stage of the shield failed to inflate, the demonstrator survived the orbital reentry and was recovered.[43][44] The subsequent missions flown on the Volna rocket failed due to launcher failure.[45]

NASA IRVE[edit]

NASA launched an inflatable heat shield experimental spacecraft on 17 August 2009 with the successful first test flight of the Inflatable Re-entry Vehicle Experiment (IRVE). The heat shield had been vacuum-packed into a 15-inch (380 mm) diameter payload shroud and launched on a Black Brant 9 sounding rocket from NASA's Wallops Flight Facility on Wallops Island, Virginia. "Nitrogen inflated the 10-foot (3.0 m) diameter heat shield, made of several layers of silicone-coated [Kevlar] fabric, to a mushroom shape in space several minutes after liftoff."[42] The rocket apogee was at an altitude of 131 miles (211 km) where it began its descent to supersonic speed. Less than a minute later the shield was released from its cover to inflate at an altitude of 124 miles (200 km). The inflation of the shield took less than 90 seconds.[42]

NASA HIAD[edit]

Following the success of the initial IRVE experiments, NASA developed the concept into the more ambitious Hypersonic Inflatable Aerodynamic Decelerator (HIAD). The current design is shaped like a shallow cone, with the structure built up as a stack of circular inflated tubes of gradually increasing major diameter. The forward (convex) face of the cone is covered with a flexible thermal protection system robust enough to withstand the stresses of atmospheric entry (or re-entry).[46] [47]

Entry vehicle design considerations[edit]

There are four critical parameters considered when designing a vehicle for atmospheric entry:

1. Peak heat flux
2. Heat load
3. Peak deceleration
4. Peak dynamic pressure

Peak heat flux and dynamic pressure selects the TPS material. Heat load selects the thickness of the TPS material stack. Peak deceleration is of major importance for manned missions. The upper limit for manned return to Earth from Low Earth Orbit (LEO) or lunar return is 10 Gs.[48] For Martian atmospheric entry after long exposure to zero gravity, the upper limit is 4 Gs.[48] Peak dynamic pressure can also influence the selection of the outermost TPS material if spallation is an issue.

Starting from the principle of *conservative design*, the engineer typically considers two worst case trajectories, the undershoot and overshoot trajectories. The overshoot trajectory is typically defined as the shallowest allowable entry velocity angle prior to atmospheric skip-off. The overshoot trajectory has the highest heat load and sets the TPS thickness. The undershoot trajectory is defined by the steepest allowable trajectory. For manned missions the steepest entry angle is limited by the peak deceleration. The undershoot trajectory also has the highest peak heat flux and dynamic pressure. Consequently, the undershoot trajectory is the basis for selecting the TPS material. There is no "one size fits all" TPS material. A TPS material that is ideal for high heat flux may be too conductive (too dense) for a long duration heat load. A low density TPS material might lack the tensile strength to resist spallation if the dynamic pressure is too high. A TPS material can perform well for a specific peak heat flux, but fail catastrophically for the same peak heat flux if the wall pressure is significantly increased (this happened with NASA's R-4 test spacecraft).[48] Older TPS materials tend to be more labor-intensive and expensive to manufacture compared to modern materials.

However, modern TPS materials often lack the flight history of the older materials (an important consideration for a risk-averse designer).

Based upon Allen and Eggers discovery, maximum aeroshell bluntness (maximum drag) yields minimum TPS mass. Maximum bluntness (minimum ballistic coefficient) also yields a minimal terminal velocity at maximum altitude (very important for Mars EDL, but detrimental for military RVs). However, there is an upper limit to bluntness imposed by aerodynamic stability considerations based upon *shock wave detachment*. A shock wave will remain attached to the tip of a sharp cone if the cone's half-angle is below a critical value. This critical half-angle can be estimated using perfect gas theory (this specific aerodynamic instability occurs below hypersonic speeds). For a nitrogen atmosphere (Earth or Titan), the maximum allowed half-angle is approximately 60°. For a carbon dioxide atmosphere (Mars or Venus), the maximum allowed half-angle is approximately 70°. After shock wave detachment, an entry vehicle must carry significantly more shocklayer gas around the leading edge stagnation point (the subsonic cap). Consequently, the aerodynamic center moves upstream thus causing aerodynamic instability. It is incorrect to reapply an aeroshell design intended for Titan entry (Huygens probe in a nitrogen atmosphere) for Mars entry (Beagle-2 in a carbon dioxide atmosphere).[*citation needed*][*original research?*] Prior to being abandoned, the Soviet Mars lander program achieved one successful landing (Mars 3), on the second of three entry attempts (the others were Mars 2 and Mars 6). The Soviet Mars landers were based upon a 60° half-angle aeroshell design.

A 45 degree half-angle sphere-cone is typically used for atmospheric probes (surface landing not intended) even though TPS mass is not minimized. The rationale for a 45° half-angle is to have either aerodynamic stability from entry-to-impact (the heat shield is not jettisoned) or a short-and-sharp heat pulse followed by prompt heat shield jettison. A 45° sphere-cone design was used with the DS/2 Mars impactor and Pioneer Venus Probes.

Notable atmospheric entry accidents[edit]

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Re-entry window A- Friction with air, B- In air flight. C- Expulsion lower angle, D- Perpendicular to the entry point, E- Excess friction 6.9° to 90°, F- Repulsion of 5.5° or less, G- Explosion friction, H- plane tangential to the entry point

Not all atmospheric re-entries have been successful and some have resulted in significant disasters.

- Voskhod 2 – The service module failed to detach for some time, but the crew survived.
- Soyuz 1 – The attitude control system failed while still in orbit and later parachutes got entangled during the emergency landing sequence (entry, descent and landing (EDL) failure). Lone cosmonaut Vladimir Mikhailovich Komarov died.
- Soyuz 5 – The service module failed to detach, but the crew survived.
- Soyuz 11 – After Tri Module Sep, a valve was weakened by the blast and failed on re-entry. The cabin depressurized killing all three crew members.
- Mars Polar Lander – Failed during EDL. The failure was believed to be the consequence of a software error. The precise cause is unknown for lack of real-time telemetry.
- Space Shuttle *Columbia* during STS-1 – a combination of launch damage, protruding gap filler, and tile installation error resulted in serious damage to the orbiter, only some of which the crew was privy to. Had the crew known the true extent of the damage before attempting re-entry, they would have flown the shuttle to a safe altitude and then bailed out. Nevertheless, re-entry was successful, and the orbiter proceeded to a normal landing.
- Space Shuttle *Columbia* during STS-107 – The failure of an RCC panel on a wing leading edge caused by debris impact at launch led to breakup of the orbiter on reentry resulting in the deaths of all seven crew members.

Genesis entry vehicle after crash

- Genesis – The parachute failed to deploy due to a G-switch having been installed backwards (a similar error delayed parachute deployment for the Galileo Probe). Consequently, the Genesis entry vehicle crashed into the desert floor. The payload was damaged, but most scientific data were recoverable.
- Soyuz TMA-11 – The Soyuz propulsion module failed to separate properly; fallback ballistic reentry was executed that subjected the crew to forces about eight times that of gravity.[49] The crew survived.

Uncontrolled and unprotected reentries[edit]

Of satellites that reenter, approximately 10-40% of the mass of the object is likely to reach the surface of the Earth.[50] On average, about one catalogued object reenters per day.[51]

Due to the Earth's surface being primarily water, most objects that survive reentry land in one of the world's oceans. The estimated chances that a given person will get hit and injured during his/her lifetime is around 1 in a trillion.[52]

In 1978, Cosmos 954 reentered uncontrolled and crashed near Great Slave Lake in the Northwest Territories of Canada. Cosmos 954 was nuclear powered and left radioactive debris near its impact site.[53]

In 1979, Skylab reentered uncontrolled, spreading debris across the Australian Outback, damaging several buildings and killing a cow.[54][55] The re-entry was a major media event largely due to the Cosmos 954 incident, but not viewed as much as a potential disaster since it did not carry nuclear fuel. The city of Esperance, Western Australia, issued a fine for littering to the United States, which was finally paid 30 years later (not by NASA, but by privately collected funds from radio listeners).[56] NASA had originally hoped to use a Space Shuttle mission to either extend its life or enable a controlled reentry, but delays in the program combined with unexpectedly high solar activity made this impossible.[57][58]

On February 7, 1991 Salyut 7 underwent uncontrolled reentry with Kosmos 1686. It reentered over Argentina and scattered much of its debris over the town of Capitan Bermudez.[59][60][61]

Deorbit disposal[edit]

Salyut 1, the world's first space station, was deliberately de-orbited into the Pacific Ocean in 1971 following the Soyuz 11 accident. Its successor, Salyut 6, was de-orbited in a controlled manner as well.

On June 4, 2000 the Compton Gamma Ray Observatory was deliberately de-orbited after one of its gyroscopes failed. The debris that did not burn up fell harmlessly into the Pacific Ocean. The observatory was still operational, but the failure of another gyroscope would have made de-orbiting much more difficult and dangerous. With some controversy, NASA decided in the interest of public safety that a controlled crash was preferable to letting the craft come down at random.

In 2001, the Russian Mir space station was deliberately de-orbited, and broke apart in the fashion expected by the command center during atmospheric re-entry. Mir entered the Earth's atmosphere on March 23, 2001, near Nadi, Fiji, and fell into the South Pacific Ocean.

On February 21, 2008, a disabled US spy satellite, USA 193, was hit at an altitude of approximately 246 kilometers (153 mi) with an SM-3 missile fired from the U.S. Navy cruiser*Lake Erie* off the coast of Hawaii. The satellite was inoperative, having failed to reach its intended orbit when it was launched in 2006. Due to its rapidly deteriorating orbit it was destined for uncontrolled reentry within a month. United States Department of Defense expressed concern that the 1,000-pound (450 kg) fuel tank containing highly toxic hydrazinemight survive reentry to reach the Earth's surface intact. Several governments including those of Russia, China, and Belarus protested the action as a thinly-veiled demonstration of US anti-satellite capabilities.[62] China had previously caused an international incident when it tested an anti-satellite missile in 2007.

On September 7, 2011, NASA announced the impending uncontrolled re-entry of Upper Atmosphere Research Satellite and noted that there was a small risk to the public.[63] The decommissioned satellite reentered the atmosphere on September 24, 2011, and some pieces are presumed to have crashed into the South Pacific Ocean over a debris field 500 miles (800 km) long.[64]

Closeup of Gemini 2heat shield

Cross section of Gemini 2 heat shield

Successful atmospheric re-entries from orbital velocities[edit]

Manned orbital re-entry, by country/governmental entity

Parachute

From Wikipedia, the free encyclopedia

This article is about the device. For sports and other activities involving a parachute, see Parachuting. For other uses, see Parachute (disambiguation).

"Parachutes" redirects here. For the album by Coldplay, see Parachutes (album).

It has been suggested that Canopy (parachute) be merged into this article. (Discuss) Proposed since March 2017.

Parachutes deploying.

A parachute is a device used to slow the motion of an object through an atmosphere by creating drag (or in the case of ram-air parachutes, aerodynamic lift). Parachutes are usually made out of light, strong fabric, originally silk, now most commonly nylon. They are typically dome-shaped, but vary, with rectangles, inverted domes, and others found. A variety of loads are attached to parachutes, including people, food, equipment, space capsules, and bombs.

A drogue chute is used to aid horizontal deceleration of a vehicle such as fixed-wing aircraft and drag racer); provide stability, as to certain types of light aircraft in distress,[1][2] tandem free-fall; and as a pilot triggering deployment a larger parachute.

Drag (physics)

From Wikipedia, the free encyclopedia

(Redirected from Atmospheric drag)

In fluid dynamics, **drag** (sometimes called **air resistance**, a type of friction, or **fluid resistance**, another type of friction or fluid friction) is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid.[1] This can exist between two fluid layers (or surfaces) or a fluid and a solid surface. Unlike other resistive forces, such as dry friction, which are nearly independent of velocity, drag forces depend on velocity.[2][3] Drag force is proportional to the velocity for a laminar flow and the squared velocity for a turbulent flow. Even though the ultimate cause of a drag is viscous friction, the turbulent drag is independent of viscosity.[4]

Drag forces always decrease fluid velocity relative to the solid object in the fluid's path

Examples of drag[edit]

Examples of drag include the component of the net aerodynamic or hydrodynamic force acting opposite to the direction of movement of a solid object such as cars, aircraft[3] and boat hulls; or acting in the same geographical direction of motion as the solid, as for sails attached to a down wind sail boat, or in intermediate directions on a sail depending on points of sail.[5][6][7] In the case of viscous drag of fluid in a pipe, drag force on the immobile pipe decreases fluid velocity relative to the pipe.[8][9]

In physics of sports, the drag force is necessary to explain the performance of runners, particularly of sprinters.[10]

Types of drag[edit]

Types of drag are generally divided into the following categories:

The phrase *parasitic drag* is mainly used in aerodynamics, since for lifting wings drag it is in general small compared to lift. For flow around bluff bodies, form and interference drags often dominate, and then the qualifier "parasitic" is meaningless.[*citation needed*]

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Further, lift-induced drag is only relevant when wings or a lifting body are present, and is therefore usually discussed either in aviation or in the design of semi-planing or planing hulls. Wave drag occurs either when a solid object is moving through a fluid at or near the speed of sound or when a solid object is moving along a fluid boundary, as in surface waves.

Drag coefficient C_d for a sphere as a function of Reynolds number *Re*, as obtained from laboratory experiments. The dark line is for a sphere with a smooth surface,

while the lighter line is for the case of a rough surface

Note that the power needed to push an object through a fluid increases as the cube of the velocity. A car cruising on a highway at 50 mph (80 km/h) may require only 10 horsepower(7.5 kW) to overcome air drag, but that same car at 100 mph (160 km/h) requires 80 hp (60 kW).[16] With a doubling of speed the drag (force) quadruples per the formula. Exerting 4 times the force over a fixed distance produces 4 times as much work. At twice the speed the work (resulting in displacement over a fixed distance) is done twice as fast. Since power is the rate of doing work, 4 times the work done in half the time requires 8 times the power.

Velocity of a falling object[edit]

Main article: Terminal velocity

An object falling through viscous medium accelerates quickly towards its terminal speed, approaching gradually as the speed gets nearer to the terminal speed. Whether the object experiences turbulent or laminar drag changes the characteristic shape of the graph with turbulent flow resulting in a constant acceleration for a larger fraction of its accelerating time.

The velocity as a function of time for an object falling through a non-dense medium, and released at zero relative-velocity $v = 0$ at time $t = 0$, is roughly given by a function involving a hyperbolic tangent (tanh):

The hyperbolic tangent has a limit value of one, for large time t. In other words, velocity asymptotically approaches a maximum value called the terminal velocity v_t:

Induced drag *vs.*lift[21][22]

Lift-induced drag (also called **induced drag**) is drag which occurs as the result of the creation of lift on a three-dimensional lifting body, such as the wing or fuselage of an airplane. Induced drag consists of two primary components, including drag due to the creation of vortices (**vortex drag**) and the presence of additional viscous drag (**lift-induced viscous drag**). The vortices in the flow-field, present in the wake of a lifting body, derive from the turbulent mixing of air of varying pressure on the upper and lower surfaces of the body, which is a necessary condition for the creation of lift.

With other parameters remaining the same, as the lift generated by a body increases, so does the lift-induced drag. This means that as the wing's angle of attack increases the lift coefficient increases (up to a limit called the stall point) so too does the lift-induced drag. At the onset of stall, lift is abruptly decreased, as is lift-induced drag, but viscous pressure drag, a component of parasite drag, increases due to the formation of turbulent unattached flow on the surface of the body.

Parasitic drag[edit]

Main article: parasitic drag

Parasitic drag is drag caused by moving a solid object through a fluid. Parasitic drag is made up of multiple components including viscous pressure drag (**form drag**), and drag due to surface roughness (**skin friction drag**). Additionally, the presence of multiple bodies in relative proximity may incur so called **interference drag**, which is sometimes described as a component of parasitic drag.

In aviation, induced drag tends to be greater at lower speeds because a high angle of attack is required to maintain lift, creating more drag. However, as speed increases the angle of attack can be reduced and the induced drag decreases. Parasitic drag, however, increases because the fluid is flowing more quickly around protruding objects increasing friction or drag. At even higher speeds (transonic), wave drag enters the picture. Each of these forms of drag changes in proportion to the others based on speed. The combined overall drag curve therefore shows a minimum at some airspeed - an aircraft flying at this speed will be at or close to its optimal efficiency. Pilots will use this speed to maximize endurance(minimum fuel consumption), or maximize gliding range in the event of an engine failure.

Power curve in aviation[edit]

The *power curve*: form and induced drag *vs.* airspeed

The interaction of parasitic and induced drag *vs.* airspeed can be plotted as a characteristic curve, illustrated here. In aviation, this is often referred to as the *power curve*, and is important to pilots because it shows that, below a certain airspeed, maintaining airspeed counterintuitively requires *more* thrust as speed decreases, rather than less. The consequences of being "behind the curve" in flight are important and are taught as part of pilot training. At the subsonic airspeeds where the "U" shape of this curve is significant, wave drag has not yet become a factor, and so it is not shown in the curve.

Wave drag in transonic and supersonic flow[edit]

Qualitative variation in Cd factor with Mach number for aircraft

Main article: wave drag

Wave drag (also called **compressibility drag**) is drag that is created when a body moves in a compressible fluid and at speeds that are close to the speed of sound in that fluid. In aerodynamics, wave drag consists of multiple components depending on the speed regime of the flight.

In transonic flight (Mach numbers greater than about 0.8 and less than about 1.4), wave drag is the result of the formation of shockwaves in the fluid, formed when local areas of supersonic (Mach number greater than 1.0) flow are created. In practice, supersonic flow occurs on bodies traveling well below the speed of sound, as the local speed of air increases as it accelerates over the body to speeds above Mach 1.0. However, full supersonic flow over the vehicle will not develop until well past Mach 1.0. Aircraft flying at transonic speed often incur wave drag through the normal course of operation. In transonic flight, wave drag is commonly referred to as **transonic compressibility drag**. Transonic compressibility drag increases significantly as the speed of flight increases towards Mach 1.0, dominating other forms of drag at those speeds.

In supersonic flight (Mach numbers greater than 1.0), **wave drag** is the result of shockwaves present in the fluid and attached to the body, typically **oblique shockwaves** formed at the leading and trailing edges of the body. In highly supersonic flows, or in bodies with turning angles sufficiently large, **unattached shockwaves**, or **bow waves** will instead form. Additionally, local areas of transonic flow behind the initial shockwave may occur at lower supersonic speeds, and can lead to the development of additional, smaller shockwaves present on the surfaces of other lifting bodies, similar to those found in transonic flows. In supersonic flow regimes, **wave drag** is commonly separated into two components, **supersonic lift-dependent wave drag** and **supersonic volume-dependent wave drag**.

The closed form solution for the minimum wave drag of a body of revolution with a fixed length was found by Sears and Haack, and is known as the **Sears-Haack Distribution**. Similarly, for a fixed volume, the shape for minimum wave drag is the **Von Karman Ogive**.

Busemann's Biplane is not, in principle, subject to wave drag at all when operated at its design speed, but is incapable of generating lift.

d'Alembert's paradox[edit]

Main article: d'Alembert's paradox

In 1752 d'Alembert proved that potential flow, the 18th century state-of-the-art inviscid flow theory amenable to mathematical solutions, resulted in the prediction of zero drag. This was in contradiction with experimental evidence, and became known as d'Alembert's paradox. In the 19th century the Navier–Stokes equations for the description of viscous flow were developed by Saint-Venant, Navier and Stokes. Stokes derived the drag around a sphere at very low Reynolds numbers, the result of which is called Stokes' law.[23]

In the limit of high Reynolds numbers, the Navier–Stokes equations approach the inviscid Euler equations, of which the potential-flow solutions considered by d'Alembert are solutions. However, all experiments at high Reynolds numbers showed there is drag. Attempts to construct inviscid steady flow solutions to the Euler equations, other than the potential flow solutions, did not result in realistic results.[23]

The notion of boundary layers—introduced by Prandtl in 1904, founded on both theory and experiments—explained the causes of drag at high Reynolds numbers. The boundary layer is the thin layer of fluid close to the object's boundary, where viscous effects remain important even when the viscosity is very small (or equivalently the Reynolds number is very large).[23]

Orbital maneuver

From Wikipedia, the free encyclopedia

In spaceflight, an orbital maneuver (otherwise known as a burn) is the use of propulsion systems to change the orbit of a spacecraft. For spacecraft far from Earth (for example those in orbits around the Sun) an orbital maneuver is called a deep-space maneuver (DSM).[not verified in body]

The rest of the flight, especially in a transfer orbit, is called coasting.

General[edit]

Rocket equation[edit]

Main article: Tsiolkovsky rocket equation

Oberth effect[edit]

Main article: Oberth effect

In astronautics, the **Oberth effect** is where the use of a rocket engine when travelling at high speed generates much more useful energy than one at low speed. Oberth effect occurs because the propellant has more usable energy (due to its kinetic energy on top of its chemical potential energy) and it turns out that the vehicle is able to employ this kinetic energy to generate more mechanical power. It is named after Hermann Oberth, the Austro-Hungarian-born, German physicist and a founder of modern rocketry, who apparently first described the effect.[1]

Oberth effect is used in a **powered flyby** or **Oberth maneuver** where the application of an impulse, typically from the use of a rocket engine, close to a gravitational body (where the gravity potential is low, and the speed is high) can give much more change in kinetic energy and final speed (i.e. higher specific energy) than the same impulse applied further from the body for the same initial orbit.

Since the Oberth maneuver happens in a very limited time (while still at low altitude), to generate a high impulse the engine necessarily needs to achieve high thrust (impulse is by definition the time multiplied by thrust). Thus the Oberth effect is far less useful for low-thrust engines, such as ion thrusters.

Historically, a lack of understanding of this effect led investigators to conclude that interplanetary travel would require completely impractical amounts of propellant, as without it, enormous amounts of energy are needed.[1]

Gravitational assist[edit]

Main article: Gravity assist

The trajectories that enabled NASA's twin Voyager spacecraft to tour the four gas giant planets and achieve velocity to escape our solar system

In orbital mechanics and aerospace engineering, a **gravitational slingshot**, **gravity assist maneuver**, or **swing-by** is the use of the relative movement and gravity of a planet or other celestial body to alter the path and speed of a spacecraft, typically in order to save propellant, time, and expense. Gravity assistance can be used to accelerate, decelerate and/or re-direct the path of a spacecraft.

The "assist" is provided by the motion (orbital angular momentum) of the gravitating body as it pulls on the spacecraft.[2] The technique was first proposed as a mid-course manoeuvre in 1961, and used by interplanetary probes from *Mariner 10* onwards, including the two *Voyager*probes' notable fly-bys of Jupiter and Saturn.

Transfer orbits[edit]

Orbit insertion is a general term for a maneuver that is more than a small correction. It may be used for a maneuver to change a transfer orbitor an ascent orbit into a stable one, but also to change a stable orbit into a descent: *descent orbit insertion*. Also the term **orbit injection** is used, especially for changing a stable orbit into a transfer orbit, e.g. trans-lunar injection (TLI), trans-Mars injection (TMI) and trans-Earth injection (TEI).

Hohmann transfer[edit]

Hohmann Transfer Orbit

Main article: Hohmann transfer orbit

In orbital mechanics, the **Hohmann transfer orbit** is an elliptical orbit used to transfer between two circular orbits of different altitudes, in the same plane.

The orbital maneuver to perform the Hohmann transfer uses two engine impulses which move a spacecraft onto and off the transfer orbit. This maneuver was named after Walter Hohmann, the German scientist who published a description of it in his 1925 book *Die Erreichbarkeit der Himmelskörper* (*The Accessibility of Celestial Bodies*).[3] Hohmann was influenced in part by the German science fiction author Kurd Laßwitz and his 1897 book *Two Planets*.[*citation needed*]

Bi-elliptic transfer[edit]

Bi-elliptic transfer from blue to red circular orbit

Main article: Bi-elliptic transfer

In astronautics and aerospace engineering, the **bi-elliptic transfer** is an orbital maneuver that moves a spacecraft from one orbit to another and may, in certain situations, require less delta-v than a Hohmann transfer maneuver.

The bi-elliptic transfer consists of two half elliptic orbits. From the initial orbit, a delta-v is applied boosting the spacecraft into the first transfer orbit with

an apoapsis at some point away from the central body. At this point, a second

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delta-v is applied sending the spacecraft into the second elliptical orbit with periapsis at the radius of the final desired orbit, where a third delta-v is performed, injecting the spacecraft into the desired orbit.[*citation needed*]

While they require one more engine burn than a Hohmann transfer and generally requires a greater travel time, some bi-elliptic transfers require a lower amount of total delta-v than a Hohmann transfer when the ratio of final to initial semi-major axis is 11.94 or greater, depending on the intermediate semi-major axis chosen.[4]

The idea of the bi-elliptical transfer trajectory was first published by Ary Sternfeld in 1934.[5]

Low energy transfer[edit]

Main article: low energy transfer

A **low energy transfer**, or low energy trajectory, is a route in space which allows spacecraft to change orbits using very little fuel.[6][7] These routes work in the Earth-Moon system and also in other systems, such as traveling between the satellites of Jupiter. The drawback of such trajectories is that they take much longer to complete than higher energy (more fuel) transfers such as Hohmann transfer orbits.

Low energy transfer are also known as weak stability boundary trajectories, or ballistic capture trajectories.

Low energy transfers follow special pathways in space, sometimes referred to as the Interplanetary Transport Network. Following these pathways allows for long distances to be traversed for little expenditure of delta-v.

Orbital inclination change[edit]

Main article: orbital inclination change

Orbital inclination change is an orbital maneuver aimed at changing the inclination of an orbiting body's orbit. This maneuver is also known as an orbital plane change as the plane of the orbit is tipped. This maneuver requires a change in the orbital velocity vector (delta v) at the orbital nodes (i.e. the point where the initial and desired orbits intersect, the line of orbital nodes is defined by the intersection of the two orbital planes).

In general, inclination changes can require a great deal of delta-v to perform, and most mission planners try to avoid them whenever possible to conserve fuel. This is typically achieved by launching a spacecraft directly into the desired inclination, or as close to it as possible so as to minimize any inclination change required over the duration of the spacecraft life.

Maximum efficiency of inclination change is achieved at apoapsis, (or apogee),

where orbital velocity is the lowest. In some cases, it may require less total delta v to raise the satellite into a higher orbit, change the orbit plane at the higher apogee, and then lower the satellite to its original altitude.[8]

Constant Thrust Trajectory[edit]

Constant-thrust and constant-acceleration trajectories involve the spacecraft firing its engine in a prolonged constant burn. In the limiting case where the vehicle acceleration is high compared to the local gravitational acceleration, the spacecraft points straight toward the target (accounting for target motion), and remains accelerating constantly under high thrust until it reaches its target. In this high-thrust case, the trajectory approaches a straight line. If it is required that the spacecraft rendezvous with the target, rather than performing a flyby, then the spacecraft must flip its orientation halfway through the journey, and decelerate the rest of the way.

In the constant-thrust trajectory,[9] the vehicle's acceleration increases during thrusting period, since the fuel use means the vehicle mass decreases. If, instead of constant thrust, the vehicle has constant acceleration, the engine thrust must decrease during the trajectory.

This trajectory requires that the spacecraft maintain a high acceleration for long durations. For interplanetary transfers, days, weeks or months of constant thrusting may be required. As a result, there are no currently available spacecraft propulsion systems capable of using this trajectory. It has been suggested that some forms of nuclear (fission or fusion based) or antimatter powered rockets would be capable of this trajectory.

Rendezvous and docking[edit]

Orbit phasing[edit]

Main article: Orbit phasing

In astrodynamics **orbit phasing** is the adjustment of the time-position of spacecraft along its orbit, usually described as adjusting the orbiting spacecraft's true anomaly.

Space rendezvous and docking[edit]

Main article: Space rendezvous

Gemini 7 photographed from Gemini 6 in 1965

A **space rendezvous** is an orbital maneuver during which two spacecraft, one of which is often a space station, arrive at the same orbit and approach to a very close distance (e.g. within visual contact). Rendezvous requires a precise match of the orbital velocities of the two spacecraft, allowing them to remain at a constant distance through orbital station-keeping. Rendezvous may or may not be followed by docking or berthing, procedures which bring the spacecraft into physical contact and create a link between them.

Spacecraft

From Wikipedia, the free encyclopedia

"Spaceship" redirects here. For other uses, see Spaceship (disambiguation).

"Rocket ship" redirects here. For other uses, see Rocket ship (disambiguation).

"Orbital vehicle" and "Orbital Vehicle" redirect here. For the Indian manned spacecraft, see ISRO Orbital Vehicle.

More than 100 Soviet and Russian Soyuz manned spacecraft (TMA version shown) have flown since 1967 and now support the International Space Station.

Columbia's first launch on the mission STS-1

The US Space Shuttle flew 135 times from 1981 to 2011, supporting Spacelab, Mir, and the ISS. (Columbia's first launch, which had a white external tank, shown)

A spacecraft is a vehicle or machine designed to fly in outer space. Spacecraft are used for a variety of purposes, including communications, earth observation, meteorology, navigation, space colonization, planetary exploration, and transportation of humans and cargo.

On a sub-orbital spaceflight, a spacecraft enters space and then returns to the surface, without having gone into an orbit. For orbital spaceflights, spacecraft enter closed orbits around the Earth or around other celestial bodies. Spacecraft used for human spaceflight carry people on board as crew or passengers from start or on orbit (space stations) only, whereas those used for robotic space missions operate either autonomously or telerobotically. Robotic spacecraft used to support scientific research are space probes. Robotic spacecraft that remain in orbit around a planetary body are artificial satellites. Only a handful of interstellar probes, such as Pioneer 10 and 11, Voyager 1 and 2, and New Horizons, are on trajectories that leave the Solar System.

Orbital spacecraft may be recoverable or not. By method of reentry to Earth they may be divided in non-winged space capsules and winged spaceplanes.

Humanity has achieved space flight but only a few nations have the technology for orbital launches, including: Russia (RSA or "Roscosmos"), the United States (NASA), the member states of the European Space Agency (ESA), Japan (JAXA), Iran (ISA), India (ISRO), and China (CNSA).

History[edit]

See also: History of spaceflight

The first artificial satellite, Sputnik 1. It was launched by the Soviet Union

Sputnik 1 was the first artificial satellite. It was launched into an elliptical low Earth orbit (LEO) by the Soviet Union on 4 October 1957. The launch ushered in new political, military, technological, and scientific developments; while the Sputnik launch was a single event, it marked the start of the Space Age.[1][2] Apart from its value as a technological first, Sputnik 1 also helped to identify the upper atmospheric layer's density, through measuring the satellite's orbital changes. It also provided data on radio-signal distribution in the ionosphere. Pressurized nitrogen in the satellite's false body provided the first opportunity for meteoroid detection. Sputnik 1 was launched during the International Geophysical Year from Site No.1/5, at the 5th Tyuratam range, in Kazakh SSR (now at the Baikonur Cosmodrome). The satellite travelled at 29,000 kilometers (18,000 mi) per hour, taking 96.2 minutes to complete an orbit, and emitted radio signals at 20.005 and 40.002 MHz

While Sputnik 1 was the first spacecraft to orbit the Earth, other man-made objects had previously reached an altitude of 100 km, which is the height required by the international organization Fédération Aéronautique Internationale to count as a spaceflight. This altitude is called the Kármán line. In particular, in the 1940s there were several test launches of the V-2 rocket, some of which reached altitudes well over 100 km.

Past and present spacecraft[edit]

Manned spacecraft[edit]

See also: List of manned spacecraft and Human spaceflight

Apollo 17 Command Module in Lunar orbit

As of 2016, only three nations have flown manned spacecraft: USSR/Russia, USA, and China. The first manned spacecraft was Vostok 1, which carried Soviet cosmonaut Yuri Gagarin into space in 1961, and completed a full Earth orbit. There were five other manned missions which used a Vostok spacecraft.[3] The second manned spacecraft was named *Freedom 7*, and it performed a sub-orbital spaceflight in 1961 carrying American astronaut Alan Shepard to an altitude of just over 187 kilometers (116 mi). There were five other manned missions using Mercury spacecraft.

Other Soviet manned spacecraft include the Voskhod, Soyuz, flown unmanned as Zond/L1, L3, TKS, and the Salyut and *Mir* manned space stations. Other American manned spacecraft include the Gemini spacecraft, Apollo spacecraft, the Skylab space station, and the Space Shuttle with undetached European Spacelab and private US Spacehab space stations-modules. China developed, but did not fly Shuguang, and is currently using Shenzhou (its first manned mission was in 2003).

Except for the space shuttle, all of the recoverable manned orbital spacecraft were space capsules.

- **Manned space capsules**

American Mercury, Gemini, and Apollo spacecraft

The International Space Station, manned since November 2000, is a joint venture between Russia, the United States, Canada and several other countries.

Spaceplanes[edit]

Main article: Spaceplane

Columbia orbiter landing

Some reusable vehicles have been designed only for manned spaceflight, and these are often called spaceplanes. The first example of such was the North American X-15 spaceplane, which conducted two manned flights which reached an altitude of over 100 km in the 1960s. The first reusable spacecraft, the X-15, was air-launched on a suborbital trajectory on July 19, 1963.

The first partially reusable orbital spacecraft, a winged non-capsule, the Space Shuttle, was launched by the USA on the 20th anniversary of Yuri Gagarin's flight, on April 12, 1981. During the Shuttle era, six orbiters were built, all of which have flown in the atmosphere and five of which have flown in space. *Enterprise* was used only for approach and landing tests, launching from the back of a Boeing 747

SCA and gliding to deadstick landings at Edwards AFB, California. The first Space Shuttle to fly into space was *Columbia*, followed by *Challenger*, *Discovery*, *Atlantis*, and *Endeavour*. *Endeavour* was built to replace *Challenger* when it was lost in January 1986. *Columbia* broke up during reentry in February 2003.

The first automatic partially reusable spacecraft was the *Buran*-class shuttle, launched by the USSR on November 15, 1988, although it made only one flight and this was unmanned. This spaceplane was designed for a crew and strongly resembled the U.S. Space Shuttle, although its drop-off boosters used liquid propellants and its main engines were located at the base of what would be the external tank in the American Shuttle. Lack of funding, complicated by the dissolution of the USSR, prevented any further flights of Buran. The Space Shuttle was subsequently modified to allow for autonomous re-entry in case of necessity.

Per the Vision for Space Exploration, the Space Shuttle was retired in 2011 due mainly to its old age and high cost of program reaching over a billion dollars per flight. The Shuttle's human transport role is to be replaced by Space X's Dragon V2 and Boeing's CST-100 Starliner no later than 2017. The Shuttle's heavy cargo transport role is to be replaced by expendable rockets such as the Space Launch System and SpaceX's Falcon Heavy.

Scaled Composites' SpaceShipOne was a reusable suborbital spaceplane that carried pilots Mike Melvill and Brian Binnie on consecutive flights in 2004 to win the Ansari X Prize. The Spaceship Company will build its successor SpaceShipTwo. A fleet of SpaceShipTwos operated by Virgin Galactic was planned to begin reusable private spaceflight carrying paying

Unfunded and canceled programs[edit]

The first test flight of the Delta Clipper-Experimental Advanced (DC-XA), a prototype launch system

Spacecraft under development[edit]

Subsystems[edit]

A spacecraft system comprises various subsystems, depending on the mission profile. Spacecraft subsystems comprise the spacecraft's "bus" and may include attitude determination and control (variously called ADAC, ADC, or ACS), guidance, navigation and control (GNC or GN&C), communications (comms), command and data handling (CDH or C&DH), power (EPS), thermal control (TCS), propulsion, and structures. Attached to the bus are typically payloads.

Life support

Spacecraft intended for human spaceflight must also include a life support system for the crew.

Reaction control system thrusters on the front of the U.S. Space Shuttle

Attitude control

A Spacecraft needs an attitude control subsystem to be correctly oriented in space and respond to external torques and forces properly. The attitude control subsystem consists of sensors and actuators, together with controlling algorithms. The attitude-control subsystem permits proper pointing for the science objective, sun pointing for power to the solar arrays and earth pointing for communications.

GNC

Guidance refers to the calculation of the commands (usually done by the CDH subsystem) needed to steer the spacecraft where it is desired to be. Navigation means determining a spacecraft's orbital elements or position. Control means adjusting the path of the spacecraft to meet mission requirements.

Command and data handling

The CDH subsystem receives commands from the communications subsystem, performs validation and decoding of the commands, and distributes the commands to the appropriate spacecraft subsystems and components. The CDH also receives housekeeping data and science data from the other spacecraft subsystems and components, and packages the data for storage on a data recorder or transmission to the ground via the communications subsystem. Other functions of the CDH include maintaining the spacecraft clock and state-of-health monitoring.

Further information: On-Board Data Handling

Communications

Spacecraft, both robotic and crewed, utilize various communications systems for communication with terrestrial stations as well as for communication between spacecraft in space. Technologies utilized include RF and optical communication. In addition, some spacecraft payloads are explicitly for the purpose of ground–ground communication using receiver/retransmitter electronic technologies.

Power

Spacecraft need an electrical power generation and distribution subsystem for powering the various spacecraft subsystems. For spacecraft near the Sun, solar panels are frequently used to generate electrical power. Spacecraft designed to operate in more distant locations, for example Jupiter, might employ a radioisotope thermoelectric generator(RTG) to generate electrical power. Electrical power is sent through power conditioning equipment before it passes through a power distribution unit over an electrical bus to other spacecraft components. Batteries are typically connected to the bus via a battery charge regulator, and the batteries are used to provide electrical power during periods when primary power is not available, for example when a low Earth orbit spacecraft is eclipsed by Earth.

Thermal control

Spacecraft must be engineered to withstand transit through Earth's atmosphere and the space environment. They must operate in a vacuum with temperatures potentially ranging across hundreds of degrees Celsius as well as (if subject to reentry) in the presence of plasmas. Material requirements are such that either high melting temperature, low density materials such as beryllium and reinforced carbon–carbon or (possibly due to the lower thickness requirements despite its high density) tungsten or ablative carbon–carbon composites are used. Depending on mission profile, spacecraft may also need to operate on the surface of another planetary body. The thermal control subsystem can be passive, dependent on the selection of materials with specific radiative properties. Active thermal control makes use of electrical heaters and certain actuators such as louvers to control temperature ranges of equipments within specific ranges.

Spacecraft propulsion

Spacecraft may or may not have a propulsion subsystem, depending on whether or not the mission profile calls for propulsion. The *Swift* spacecraft is an example of a spacecraft that does not have a propulsion subsystem. Typically though, LEO spacecraft include a propulsion subsystem for altitude adjustments (drag make-up maneuvers) and inclinationadjustment maneuvers. A propulsion system is also needed for spacecraft that perform momentum management maneuvers. Components of a conventional propulsion subsystem include fuel, tankage, valves, pipes, and thrusters. The thermal control system interfaces with the propulsion subsystem by monitoring the temperature of those components, and by preheating tanks and thrusters in preparation for a spacecraft maneuver.

Structures

Spacecraft must be engineered to withstand launch loads imparted by the launch vehicle, and must have a point of attachment for all the other subsystems. Depending on mission profile, the structural subsystem might need to withstand loads imparted by entry into the atmosphere of another planetary body, and landing on the surface of another planetary body.

Payload

The payload depends on the mission of the spacecraft, and is typically regarded as the part of the spacecraft "that pays the bills". Typical payloads could include scientific instruments (cameras, telescopes, or particle detectors, for example), cargo, or a human crew.

Ground segment

Main article: Ground segment

The ground segment, though not technically part of the spacecraft, is vital to the operation of the spacecraft. Typical components of a ground segment in use during normal operations include a mission operations facility where the flight operations team conducts the operations of the spacecraft, a data processing and storage facility, ground stationsto radiate signals to and receive signals from the spacecraft, and a voice and data communications network to connect all mission elements.[6]

Launch vehicle

The launch vehicle propels the spacecraft from Earth's surface, through the atmosphere, and into an orbit, the exact orbit being dependent on the mission configuration. The launch vehicle may be expendable or reusable.

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Rocket

From Wikipedia, the free encyclopedia

For other uses, see Rocket (disambiguation).

A Soyuz-U, at Baikonur cosmodrome's Site 1/5 in Kazakhstan

A rocket (from Italian rocchetto "bobbin")[nb 1][1] is a missile, spacecraft, aircraft or other vehicle that obtains thrust from a rocket engine. Rocket engine exhaust is formed entirely from propellant carried within the rocket before use.[2] Rocket engines work by action and reaction and push rockets forward simply by expelling their exhaust in the opposite direction at high speed, and can therefore work in the vacuum of space.

In fact, rockets work more efficiently in space than in an atmosphere. Multistage rockets are capable of attaining escape velocity from Earth and therefore can achieve unlimited maximum altitude. Compared with airbreathing engines, rockets are lightweight and powerful and capable of generating large accelerations. To control their flight, rockets rely on momentum, airfoils, auxiliary reaction engines, gimballed thrust, momentum wheels, deflection of the exhaust stream, propellant flow, spin, and/or gravity.

Rockets for military and recreational uses date back to at least 13th century China.[3] Significant scientific, interplanetary and industrial use did not occur until the 20th century, when rocketry was the enabling technology for the Space Age, including setting foot on the Earth's moon. Rockets are now used for fireworks, weaponry, ejection seats, launch vehicles for artificial satellites, human spaceflight, and space exploration.

Chemical rockets are the most common type of high power rocket, typically creating a high speed exhaust by the combustion of fuel with an oxidizer. The stored propellant can be a simple pressurized gas or a single liquid fuel that disassociates in the presence of a catalyst (monopropellants), two liquids that spontaneously react on contact (hypergolic propellants), two liquids that must be ignited to react, a solid combination of fuel with oxidizer (solid fuel), or solid fuel with liquid oxidizer (hybrid propellant system). Chemical rockets store a large amount of energy in an easily released form, and can be very dangerous. However, careful design, testing, construction and use minimizes risks

History

Main article: History of rockets

Further information: Timeline of rocket and missile technology

The first gunpowder-powered rockets were developed in the medieval Chinese Song dynasty, by the 13th century. The Chinese rocket technology was adopted by the Mongols and the invention was spread via the Mongol invasions to the Middle East and Europe in the mid 13th century.[4] The first gunpowder-powered rockets were developed during the Song dynasty and by the 13th century. The Chinese rocket technology was adopted by the Mongols and the invention was spread via the Mongol invasions to the Middle East and Europe in the mid 13th century.[5] Rockets are recorded to have been used by the Song navy in a military exercise dated to 1245. Internal-combustion rocket propulsion is mentioned in a reference to 1264, recording that the 'ground-rat,' a type of firework, had frightened the Empress-Mother Gongsheng at a feast held in her honor by her son the Emperor Lizong.[6]Subsequently, rockets are included in the military treatise *Huolongjing*, also known as the Fire Drake Manual, written by the Chinese artillery officer Jiao Yu in the mid-14th century. This text mentions the first known multistage rocket, the 'fire-dragon issuing from the water' (huo long chu shui), thought to have been used by the Chinese navy.[7]

Medieval and early modern rockets were used militarily as incendiary weapons in sieges. Between 1270 and 1280, Hasan al-Rammah wrote *al-furusiyyah wa al-manasib al-harbiyya*(*The Book of Military Horsemanship and Ingenious War Devices*), which included 107 gunpowder recipes, 22 of which are for rockets.[8][9] In Europe, Konrad Kyeser described rockets in his military treatise *Bellifortis* around 1405.[10]

Drawing of a Chinese soldier lighting a rocket's fuse (1890)

Depiction of a rocket (1405)

William Congreve at the bombardment of Copenhagen(1807)

The name "rocket" comes from the Italian *rocchetta*, meaning "bobbin" or "little spindle", given due to the similarity in shape to the bobbin or spool used to hold the thread to be fed to a spinning wheel. The Italian term was adopted into German in the mid 16th century by Leonhard Fronspergerand Conrad Haas, and by the early 17th century into English.[1] *Artis Magnae Artilleriae pars prima*, an important early modern work on rocket artillery, by Kazimierz Siemienowicz, was first printed in Amsterdam in 1650.

The first iron-cased rockets were developed in the late 18th century in the Kingdom of Mysore (currently Part of India) by Tipu Sultan[11]. The congreve rocket was a British military weapon designed and developed by Sir William Congreve in 1804, based directly on Mysorean rockets.

In 1814, Francis Scott Key wrote the line "rockets' red glare" while held captive on a British ship that was laying siege to Fort McHenry. The rockets he witnessed were an invention of William Congreve, who built a compressed-powder rocket encased in metal, increasing the effective range from 100 to 2,000 yards, first used in the Napoleonic Wars.[12] The first mathematical treatment of the dynamics of rocket propulsion is due to William Moore (1813). In 1815, Alexander Dmitrievich Zasyadko constructed rocket-launching platforms, which allowed rockets to be fired in salvos (6 rockets at a time), and gun-laying devices.

William Hale in 1844 greatly increased the accuracy of rocket artillery. The Congreve rocket was further improved by Edward Mounier Boxer in 1865.

Konstantin Tsiolkovsky (1903) first speculated on the possibility of manned spaceflight with rocket technology. Robert Goddard in 1920 published proposed improvements to rocket technology in *A Method of Reaching Extreme Altitudes*. In 1923, Hermann Oberth (1894–1989) published *Die Rakete zu den Planetenräumen*("The Rocket into Planetary Space")

Goddard with a liquid oxygen-gasoline rocket (1926)

Modern rockets originated when Goddard attached a supersonic (de Laval) nozzle to the combustion chamber of a liquid-propellant rocket. These nozzles turn the hot gas from the combustion chamber into a cooler, hypersonic, highly directed jet of gas, more than doubling the thrust and raising the engine efficiency from 2% to 64%. Use of liquid propellants instead of gunpowder greatly improved the effectiveness of rocket artillery in World War II, and opened up the possibility of manned spaceflight after 1945.

In 1943, production of the V-2 rocket began in Germany. In parallel with the guided missile programme, rockets were also used on aircraft, either for assisting horizontal take-off (RATO), vertical take-off (Bachem Ba 349 "Natter") or for powering them (Me 163, see list of World War II guided missiles of Germany). The Allies' rocket programs were less sophisticated, relying mostly on unguided missiles like the Soviet Katyusha rocket. The Americans captured a large number of German rocket scientists, including Wernher von Braun, and brought them to the United States as part of Operation Paperclip. After the war, rockets were used to study high-altitude conditions, by radio telemetry of temperature and pressure of the atmosphere, detection of cosmic rays, and further research; notably the Bell X-1, the first manned vehicle to break the sound barrier. Independently, in the Soviet Union's space program research continued under the leadership of the chief designer Sergei Korolev.

During the Cold War, rockets became extremely important militarily as modern intercontinental ballistic missiles (ICBMs). The 1960s became the decade of rapid development of rocket technology particularly in the Soviet Union (Vostok, Soyuz, Proton) and in the United States (e.g. the X-15). Rockets were now used for space exploration, with the American manned programs Project Mercury, Project Gemini and later the Apollo programmeculminated in 1969 with the first manned landing on the moon via the Saturn V.

Types

Vehicle configurations

Saturn V is the biggest rocket to have successfully flown.

Rocket vehicles are often constructed in the archetypal tall thin "rocket" shape that takes off vertically, but there are actually many different types of rockets including:[13][14]

- tiny models such as balloon rockets, water rockets, skyrockets or small solid rockets that can be purchased at a hobby store
- missiles
- space rockets such as the enormous Saturn V used for the Apollo program
- rocket cars
- rocket bike[15]
- rocket-powered aircraft (including rocket assisted takeoff of conventional aircraft- RATO)
- rocket sleds
- rocket trains
- rocket torpedoes[16][17]
- rocket-powered jet packs[18]
- rapid escape systems such as ejection seats and launch escape systems
- space probes

Launch of *Apollo 15* Saturn Vrocket: $T - 30$ s through $T + 40$ s

Design

A rocket design can be as simple as a cardboard tube filled with black powder, but to make an efficient, accurate rocket or missile involves overcoming a number of difficult problems. The main difficulties include cooling the combustion chamber, pumping the fuel (in the case of a liquid fuel), and controlling and correcting the direction of motion.[19]

Components

Rockets consist of a propellant, a place to put propellant (such as a propellant tank), and a nozzle. They may also have one or more rocket engines, directional stabilization device(s)(such as fins, vernier engines or engine gimbals for thrust vectoring, gyroscopes) and a structure (typically monocoque) to hold these components together. Rockets intended for high speed atmospheric use also have an aerodynamic fairing such as a nose cone, which usually holds the payload.[20]

As well as these components, rockets can have any number of other components, such as wings (rocketplanes), parachutes, wheels (rocket cars), even, in a sense, a person (rocket belt). Vehicles frequently possess navigation systems and guidance systems that typically use satellite navigation and inertial navigation systems.

Engines

Main article: Rocket engine

Viking 5C rocket engine

Rocket engines employ the principle of jet propulsion.[2] The rocket engines powering rockets come in a great variety of different types; a comprehensive list can be found in rocket engine. Most current rockets are chemically powered rockets (usually internal combustion engines,[21] but some employ a decomposing monopropellant) that emit a hot exhaust gas. A rocket engine can use gas propellants, solid propellant, liquid propellant, or a hybrid mixture of both solid and liquid. Some rockets use heat or pressure that is supplied from a source other than the chemical reaction of propellant(s), such as steam rockets, solar thermal rockets, nuclear thermal rocket engines or simple pressurized rockets such as water rocket or cold gas thrusters. With combustive propellants a chemical reaction is initiated between the fuel and the oxidizer in the combustionchamber, and the resultant hot gases accelerate out of a rocket engine nozzle (or nozzles) at the rearward-facing end of the rocket. The accelerationof these gases through the engine exerts force ("thrust") on the combustion chamber and nozzle, propelling the vehicle (according to Newton's Third Law). This actually happens because the force (pressure times area) on the combustion chamber wall is unbalanced by the nozzle opening; this is not the case in any other direction. The shape of the nozzle also generates force by directing the exhaust gas along the axis of the rocket.[2]

Propellant

Main article: Rocket propellant

Gas Core light bulb

Rocket propellant is mass that is stored, usually in some form of propellant tank or casing, prior to being used as the propulsive mass that is ejected from a rocket engine in the form of a fluid jet to produce thrust.[2] For chemical rockets often the propellants are a fuel such as liquid hydrogen or kerosene burned with an oxidizer such as liquid oxygen or nitric acid to produce large volumes of very hot gas. The oxidiser is either kept separate and mixed in the combustion chamber, or comes premixed, as with solid rockets.

Sometimes the propellant is not burned but still undergoes a chemical reaction, and can be a 'monopropellant' such as hydrazine, nitrous oxide or hydrogen peroxide that can be catalytically decomposed to hot gas.

Alternatively, an inert propellant can be used that can be externally heated, such as in steam rocket, solar thermal rocket or nuclear thermal rockets.[2]

For smaller, low performance rockets such as attitude control thrusters where high performance is less necessary, a pressurised fluid is used as propellant that simply escapes the spacecraft through a propelling nozzle.[2]

Uses

Rockets or other similar reaction devices carrying their own propellant must be used when there is no other substance (land, water, or air) or force (gravity, magnetism, light) that a vehicle may usefully employ for propulsion, such as in space. In these circumstances, it is necessary to carry all the propellant to be used.

However, they are also useful in other situations:

Military

Main article: Missile

A Trident II missilelaunched from sea.

Some military weapons use rockets to propel warheads to their targets. A rocket and its payload together are generally referred to as a *missile* when the weapon has a guidance system (not all missiles use rocket engines, some use other engines such as jets) or as a *rocket* if it is unguided. Anti-tank and anti-aircraft missiles use rocket engines to engage targets at high speed at a range of several miles, while intercontinental ballistic missiles can be used to deliver multiple nuclear warheads from thousands of miles, and anti-ballistic missiles try to stop them. Rockets have also been tested for reconnaissance, such as the Ping-Pong rocket, which was launched to surveil enemy targets, however, recon rockets have never come into wide use in the military.

Science and research

A Bumper sounding rocket

See also: Space probe

Sounding rockets are commonly used to carry instruments that take readings from 50 kilometers (31 mi) to 1,500 kilometers (930 mi) above the surface of the Earth.[22]

Rocket engines are also used to propel rocket sleds along a rail at extremely high speed. The world record for this is Mach 8.5.[23]

Spaceflight

Main article: Spaceflight

Larger rockets are normally launched from a launch pad that provides stable support until a few seconds after ignition. Due to their high exhaust velocity—2,500 to 4,500 m/s (9,000 to 16,200 km/h; 5,600 to 10,100 mph)—rockets are particularly useful when very high speeds are required, such as orbital speed at approximately 7,800 m/s (28,000 km/h; 17,000 mph). Spacecraft delivered into orbital trajectories become artificial satellites, which are used for many commercial purposes. Indeed, rockets remain the only way to launch spacecraft into orbit and beyond.[24] They are also used to rapidly accelerate spacecraft when they change orbits or de-orbit for landing. Also, a rocket may be used to soften a hard parachute landing immediately before touchdown (see retrorocket).

Rescue

pollo LES pad abort testwith boilerplate crew module.

Rockets were used to propel a line to a stricken ship so that a Breeches buoy can be used to rescue those on board. Rockets are also used to launch emergency flares.

Some crewed rockets, notably the Saturn V[25] and Soyuz[26] have launch escape systems. This is a small, usually solid rocket that is capable of pulling the crewed capsule away from the main vehicle towards safety at a moments notice. These types of systems have been operated several times, both in testing and in flight, and operated correctly each time.

This was the case when the Safety Assurance System (Soviet nomenclature) successfully pulled away the L3 capsule during three of the four failed launches of the Soviet moon rocket, N1 vehicles 3L, 5L and 7L. In all three cases the capsule, albeit unmanned, was saved from destruction. It should be noted that only the three aforementioned N1 rockets had functional Safety Assurance Systems. The outstanding vehicle, 6L, had dummy upper stages and therefore no escape system giving the N1 booster a 100% success rate for egress from a failed launch.[27][28][29][30]

A successful escape of a manned capsule occurred when Soyuz T-10, on a mission to the Salyut 7 space station, exploded on the pad.[31]

Solid rocket propelled ejection seats are used in many military aircraft to propel crew away to safety from a vehicle when flight control is lost.[32]

Hobby, sport, and entertainment

This section needs expansion. You can help by adding to it. *(May 2016)*

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Hobbyists build and fly a wide variety of model rockets. Many companies produce model rocket kits and parts but due to their inherent simplicity some hobbyists have been known to make rockets out of almost anything. Rockets are also used in some types of consumer and professional fireworks. A Water Powered Rocket is a type of model rocket using water as its reaction mass. The pressure vessel (the engine of the rocket) is usually a used plastic soft drink bottle. The water is forced out by a pressurized gas, typically compressed air. It is an example of Newton's third law of motion.

The scale of amateur rocketry can range from a small rocket launched in one's own backyard to a rocket that reached space.[33] Amateur rocketry is split into three categories: low power, mid power, and high power.

Australia, Austria, Canada, Germany, New Zealand, Switzerland, the United Kingdom, and the United States have high power rocket associations which provide certifications to its members to fly different rocket motor sizes. While joining these organizations is not a requirement, they often provide insurance and flight waivers for their members.

Hydrogen peroxide rockets are used to power jet packs,[34] and have been used to power cars and a rocket car holds the all time (albeit unofficial) drag racing record.[35]

Corpulent Stump is the most powerful non commercial rocket ever launched on an Aerotech engine in the United Kingdom.

Noise

Workers and media witness the Water Sound Suppression System test at Launch Pad 39A.

Rocket exhaust generates a significant amount of acoustic energy. As the supersonic exhaust collides with the ambient air, shock waves are formed. The sound intensity from these shock waves depends on the size of the rocket as well as the exhaust velocity. The sound intensity of large, high performance rockets could potentially kill at close range.[36]

The Space Shuttle generates 180 dB of noise around its base.[37] To combat this, NASA developed a sound suppression system which can flow water at rates up to 900,000 gallons per minute (57 m^3/s) onto the launch pad. The water reduces the noise level from 180 dB down to 142 dB (the design requirement is 145 dB).[38] Without the sound suppression system, acoustic waves reflect off of the launch pad towards the rocket, vibrating the sensitive payload and crew. These acoustic waves can be so severe that they can destroy the rocket.

Noise is generally most intense when a rocket is close to the ground, since the noise from the engines radiates up away from the jet, as well as reflecting off the ground. This noise can be reduced somewhat by flame trenches with roofs, by water injection around the jet and by deflecting the jet at an angle.[36]

For crewed rockets various methods are used to reduce the sound intensity for the passengers, and typically the placement of the astronauts far away from the rocket engines helps significantly. For the passengers and crew, when a vehicle goes supersonic the sound cuts off as the sound waves are no longer able to keep up with the vehicle.[36]

Physics

Operation

A balloon with a tapering nozzle. In this case, the nozzle itself does not push the balloon but is pulled by it. A convergent/divergent nozzle would be better.

Main article: Rocket engine

The effect of the combustion of propellant in the rocket engine is to increase the velocity of the resulting gases to very high speeds, hence producing a thrust.[*citation needed*][*dubious* – *discuss*] Initially, the gases of combustion are sent in every direction, but only those that produce a net thrust have any effect.[*citation needed*][*dubious* – *discuss*] The ideal direction of motion of the exhaust is in the direction so as to cause thrust. At the top end of the combustion chamber the hot, energetic gas fluid cannot move forward, and so, it pushes upward against the top of the rocket engine's combustion chamber. As the combustion gases approach the exit of the combustion chamber, they increase in speed. The effect of the convergent part of the rocket engine nozzle on the high pressure fluid of combustion gases, is to cause the gases to accelerate to high speed. The higher the speed of the gases, the lower the pressure of the gas (Bernoulli's principle or conservation of energy) acting on that part of the combustion chamber. In a properly designed engine, the flow will reach Mach 1 at the throat of the nozzle. At which point the speed of the flow increases. Beyond the throat of the nozzle, a bell shaped expansion part of the engine allows the gases that are expanding to push against that part of the rocket engine. Thus, the bell part of the nozzle gives additional thrust. Simply expressed, for every action there is an equal and opposite reaction, according to Newton's third lawwith the result that the exiting gases produce the reaction of a force on the rocket causing it to accelerate the rocket.[39][nb 2]

Rocket thrust is caused by pressures acting on both the combustion chamber and nozzle

In a closed chamber, the pressures are equal in each direction and no acceleration occurs. If an opening is provided in the bottom of the chamber then the pressure is no longer acting on the missing section. This opening permits the exhaust to escape. The remaining pressures give a resultant thrust on the side opposite the opening, and these pressures are what push the rocket along.

The shape of the nozzle is important. Consider a balloon propelled by air coming out of a tapering nozzle. In such a case the combination of air pressure and viscous friction is such that the nozzle does not push the balloon but is *pulled* by it.[40] Using a convergent/divergent nozzle gives more force since the exhaust also presses on it as it expands outwards, roughly doubling the total force. If propellant gas is continuously added to the chamber then these pressures can be maintained for as long as propellant remains. Note that in the case of liquid propellant engines, the pumps moving the propellant into the combustion chamber must maintain a pressure larger than the combustion chamber -typically on the order of 100 atmospheres.[2]

As a side effect, these pressures on the rocket also act on the exhaust in the opposite direction and accelerate this exhaust to very high speeds (according to Newton's Third Law).[2] From the principle of conservation of momentum the speed of the exhaust of a rocket determines how much momentum increase is created for a given amount of propellant. This is called the rocket's *specific impulse*.[2] Because a rocket, propellant and exhaust in flight, without any external perturbations, may be considered as a closed system, the total momentum is always constant. Therefore, the faster the net speed of the exhaust in one direction, the greater the speed of the rocket can achieve in the opposite direction. This is especially true since the rocket body's mass is typically far lower than the final total exhaust mass.

Forces on a rocket in flight

Forces on a rocket in flight

The general study of the forces on a rocket is part of the field of ballistics. Spacecraft are further studied in the subfield of astrodynamics.

Flying rockets are primarily affected by the following:[41]

- Thrust from the engine(s)
- Gravity from celestial bodies
- Drag if moving in atmosphere
- Lift; usually relatively small effect except for rocket-powered aircraft

Rockets that must travel through the air are usually tall and thin as this shape gives a high ballistic coefficient and minimizes drag losses.

In addition, the inertia and centrifugal pseudo-force can be significant due to the path of the rocket around the center of a celestial body; when high enough speeds in the right direction and altitude are achieved a stable orbit or escape velocity is obtained.

These forces, with a stabilizing tail (the *empennage*) present will, unless deliberate control efforts are made, naturally cause the vehicle to follow a roughly parabolic trajectory termed a gravity turn, and this trajectory is often used at least during the initial part of a launch. (This is true even if the rocket engine is mounted at the nose.) Vehicles can thus maintain low or even zero angle of attack, which minimizes transverse stress on the launch vehicle, permitting a weaker, and hence lighter, launch vehicle.[42][43]

Drag

Main articles: Drag (physics), Gravity drag, and Aerodynamic drag

Drag is a force opposite to the direction of the rocket's motion. This decreases acceleration of the vehicle and produces structural loads. Deceleration force for fast-moving rockets are calculated using the drag equation.

Drag can be minimised by an aerodynamic nose cone and by using a shape with a high ballistic coefficient (the "classic" rocket shape—long and thin), and by keeping the rocket's angle of attack as low as possible.

During a rocket launch, as the vehicle speed increases, and the atmosphere thins, there is a point of maximum aerodynamic drag called Max Q. This determines the minimum aerodynamic strength of the vehicle, as the rocket must avoid buckling under these forces.[44]

Net thrust

A rocket jet shape varies based on external air pressure. From top to bottom:
Underexpanded
Ideally Expanded
Overexpanded
Grossly overexpanded

For a more detailed model of the net thrust of a rocket engine that includes the effect of atmospheric pressure, see Rocket_engine § Net_thrust.

A typical rocket engine can handle a significant fraction of its own mass in propellant each second, with the propellant leaving the nozzle at several kilometres per second. This means that the thrust-to-weight ratio of a rocket engine, and often the entire vehicle can be very high, in extreme cases over 100. This compares with other jet propulsion engines that can exceed 5 for some of the better[45] engines.[46]

It can be shown that the net thrust of a rocket is:

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The effective exhaust velocity is more or less the speed the exhaust leaves the vehicle, and in the vacuum of space, the effective exhaust velocity is often equal to the actual average exhaust speed along the thrust axis. However, the effective exhaust velocity allows for various losses, and notably, is reduced when operated within an atmosphere.

The rate of propellant flow through a rocket engine is often deliberately varied over a flight, to provide a way to control the thrust and thus the airspeed of the vehicle. This, for example, allows minimization of aerodynamic losses[44] and can limit the increase of *g*-forces due to the reduction in propellant load.

Total impulse

Main article: Impulse (physics)

Impulse is defined as a force acting on an object over time, which in the absence of opposing forces (gravity and aerodynamic drag), changes the momentum (integral of mass and velocity) of the object. As such, it is the best performance class (payload mass and terminal velocity capability) indicator of a rocket, rather than takeoff thrust, mass, or "power". The total impulse of a rocket (stage) burning its propellant is:[2]:27

When there is fixed thrust, this is simply:

The total impulse of a multi-stage rocket is the sum of the impulses of the individual stages.

Specific impulse

Main article: specific impulse

As can be seen from the thrust equation, the effective speed of the exhaust controls the amount of thrust produced from a particular quantity of fuel burnt per second.

An equivalent measure, the net impulse per weight unit of propellant expelled, is

called specific Impulse, , and this is one of the most important figures that

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describes a rocket's performance. It is defined such that it is related to the effective exhaust velocity by:

Delta-v (rocket equation)

A map of approximate Delta-v's around the solar system between Earth and Mars[48][49]

Main article: Tsiolkovsky rocket equation

The delta-v capacity of a rocket is the theoretical total change in velocity that a rocket can achieve without any external interference (without air drag or gravity or other forces).

When is constant, the delta-v that a rocket vehicle can provide can be calculated from the Tsiolkovsky rocket equation:[50]

When launched from the Earth practical delta-vs for a single rockets carrying payloads can be a few km/s. Some theoretical designs have rockets with delta-vs over 9 km/s.

The required delta-v can also be calculated for a particular manoeuvre; for example the delta-v to launch from the surface of the Earth to Low earth orbit is about 9.7 km/s, which leaves the vehicle with a sideways speed of about 7.8 km/s at an altitude of around 200 km. In this manoeuvre about 1.9 km/s is lost in air drag, gravity drag and gaining altitude.

The ratio is sometimes called the *mass ratio*.

Mass ratios

The Tsiolkovsky rocket equation gives a relationship between the mass ratio and the final velocity in multiples of the exhaust speed

Main article: mass ratio

Almost all of a launch vehicle's mass consists of propellant.[51] Mass ratio is, for any 'burn', the ratio between the rocket's initial mass and its final mass.[52] Everything else being equal, a high mass ratio is desirable for good performance, since it indicates that the rocket is lightweight and hence performs better, for essentially the same reasons that low weight is desirable in sports cars.

Rockets as a group have the highest thrust-to-weight ratio of any type of engine; and this helps vehicles achieve high mass ratios, which improves the performance of flights. The higher the ratio, the less engine mass is needed to be carried. This permits the carrying of even more propellant, enormously improving the delta-v. Alternatively, some rockets such as for rescue scenarios or racing carry relatively little propellant and payload and thus need only a lightweight structure and instead achieve high accelerations. For example, the Soyuz escape system can produce 20g.[26]

Achievable mass ratios are highly dependent on many factors such as propellant type, the design of engine the vehicle uses, structural safety margins and construction techniques.

The highest mass ratios are generally achieved with liquid rockets, and these types are usually used for orbital launch vehicles, a situation which calls for a high delta-v. Liquid propellants generally have densities similar to water (with the notable exceptions of liquid hydrogen and liquid methane), and these types are able to use lightweight, low pressure tanks and typically run high-performance turbopumps to force the propellant into the combustion chamber.

Some notable mass fractions are found in the following table (some aircraft are included for comparison purposes):

Staging

Spacecraft staging involves dropping off unnecessary parts of the rocket to reduce mass.

Apollo 6 while dropping the interstage ring

Main article: Multistage rocket

Thus far, the required velocity (delta-v) to achieve orbit has been unattainable by any single rocket because the propellant, tankage, structure, guidance, valves and engines and so on, take a particular minimum percentage of take-off mass that is too great for the propellant it carries to achieve that delta-v. Since Single-stage-to-orbit has so far not been achievable, orbital rockets always have more than one stage.

For example, the first stage of the Saturn V, carrying the weight of the upper stages, was able to achieve a mass ratio of about 10, and achieved a specific impulse of 263 seconds. This gives a delta-v of around 5.9 km/s whereas around 9.4 km/s delta-v is needed to achieve orbit with all losses allowed for.

This problem is frequently solved by staging — the rocket sheds excess weight (usually empty tankage and associated engines) during launch. Staging is either *serial* where the rockets light after the previous stage has fallen away, or *parallel*, where rockets are burning together and then detach when they burn out.[58]

The maximum speeds that can be achieved with staging is theoretically limited only by the speed of light. However the payload that can be carried goes down geometrically with each extra stage needed, while the additional delta-v for each stage is simply additive.

Acceleration and thrust-to-weight ratio

Main article: thrust-to-weight ratio

From Newton's second law, the acceleration, , of a vehicle is simply:

Where m is the instantaneous mass of the vehicle and is the net force acting on the rocket (mostly thrust but air drag and other forces can play a part.)

As the remaining propellant decreases, rocket vehicles become lighter and their acceleration tends to increase until the propellant is exhausted. This means that much of the speed change occurs towards the end of the burn when the vehicle is much lighter.[2] However, the thrust can be throttled to offset or vary this if needed.

Discontinuities in acceleration also occur when stages burn out, often starting at a lower acceleration with each new stage firing.

Peak accelerations can be increased by designing the vehicle with a reduced mass, usually achieved by a reduction in the fuel load and tankage and associated structures, but obviously this reduces range, delta-v and burn time. Still, for some applications that rockets are used for, a high peak acceleration applied for just a short time is highly desirable.

The minimal mass of vehicle consists of a rocket engine with minimal fuel and structure to carry it. In that case the thrust-to-weight ratio[nb 3] of the rocket engine limits the maximum acceleration that can be designed. It turns out that rocket engines generally have truly excellent thrust to weight ratios (137 for the NK-33 engine,[59] some solid rockets are over 1000[2]:442), and nearly all really high-g vehicles employ or have employed rockets.

The high accelerations that rockets naturally possess means that rocket vehicles are often capable of vertical takeoff, and in some cases, with suitable guidance and control of the engines, also vertical landing. For these operations to be done it is necessary for a vehicle's engines to provide more than the local gravitational acceleration.

Energy

Energy efficiency

Space Shuttle *Atlantis* during launch phase

Main article: propulsive efficiency

Rocket launch vehicles take-off with a great deal of flames, noise and drama, and it might seem obvious that they are grievously inefficient. However, while they are far from perfect, their energy efficiency is not as bad as might be supposed.

The energy density of a typical rocket propellant is often around one-third that of conventional hydrocarbon fuels; the bulk of the mass is (often relatively inexpensive) oxidizer. Nevertheless, at take-off the rocket has a great deal of energy in the fuel and oxidizer stored within the vehicle. It is of course desirable that as much of the energy of the propellant end up as kinetic or potential energy of the body of the rocket as possible.

Energy from the fuel is lost in air drag and gravity drag and is used for the rocket to gain altitude and speed. However, much of the lost energy ends up in the exhaust.[2]:37–38

In a chemical propulsion device, the engine efficiency is simply the ratio of the kinetic power of the exhaust gases and the power available from the chemical reaction:[2]:37–38

100% efficiency within the engine (engine efficiency) would mean that all the heat energy of the combustion products is converted into kinetic energy of the jet. This is not possible, but the near-adiabatic high expansion ratio nozzles that can be used with rockets come surprisingly close: when the nozzle expands the gas, the gas is cooled and accelerated, and an energy efficiency of up to 70% can be achieved. Most of the rest is heat energy in the exhaust that is not recovered.[2]:37–38 The high efficiency is a consequence of the fact that rocket combustion can be performed at very high temperatures and the gas is finally released at much lower temperatures, and so giving good Carnot efficiency.

However, engine efficiency is not the whole story. In common with the other jet-based engines, but particularly in rockets due to their high and typically fixed exhaust speeds, rocket vehicles are extremely inefficient at low speeds irrespective of the engine efficiency. The problem is that at low speeds, the exhaust carries away a huge amount of kinetic energyrearward. This phenomenon is

termed propulsive efficiency ( ).[2]:37–38

However, as speeds rise, the resultant exhaust speed goes down, and the overall vehicle energetic efficiency rises, reaching a peak of around 100% of the engine efficiency when the vehicle is travelling exactly at the same speed that the exhaust is emitted. In this case the exhaust would ideally stop dead in space behind the moving vehicle, taking away zero energy, and from conservation of energy, all the energy would end up in the vehicle. The efficiency then drops off again at even

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higher speeds as the exhaust ends up travelling forwards- trailing behind the vehicle.

For example, from the equation, with an of 0.7, a rocket flying at Mach 0.85 (which most aircraft cruise at) with an exhaust velocity of Mach 10, would have a predicted overall energy efficiency of 5.9%, whereas a conventional, modern, air-breathing jet engine achieves closer to 35% efficiency. Thus a rocket would need about 6x more energy; and allowing for the specific energy of rocket propellant being around one third that of conventional air fuel, roughly 18x more mass of propellant would need to be carried for the same journey. This is why rockets are rarely if ever used for general aviation.

Since the energy ultimately comes from fuel, these considerations mean that rockets are mainly useful when a very high speed is required, such as ICBMs or orbital launch. For example, NASA's space shuttle fires its engines for around 8.5 minutes, consuming 1,000 tonnes of solid propellant (containing 16% aluminium) and an additional 2,000,000 litres of liquid propellant (106,261 kg of liquid hydrogen fuel) to lift the 100,000 kg vehicle (including the 25,000 kg payload) to an altitude of 111 km and an orbital velocity of 30,000 km/h. At this altitude and velocity, the vehicle has a kinetic energy of about 3 TJ and a potential energy of roughly 200 GJ. Given the initial energy of 20 TJ,[nb 4] the Space Shuttle is about 16% energy efficient at launching the orbiter.

Thus jet engines, with a better match between speed and jet exhaust speed (such

as turbofans—in spite of their worse)—dominate for subsonic and supersonic atmospheric use, while rockets work best at hypersonic speeds. On the other hand, rockets serve in many short-range *relatively* low speed military applications where their low-speed inefficiency is outweighed by their extremely high thrust and hence high accelerations.

Oberth effect

Main article: Oberth effect

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One subtle feature of rockets relates to energy. A rocket stage, while carrying a given load, is capable of giving a particular delta-v. This delta-v means that the speed increases (or decreases) by a particular amount, independent of the initial speed. However, because kinetic energy is a square law on speed, this means that the faster the rocket is travelling before the burn the more orbital energy it gains or loses.

This fact is used in interplanetary travel. It means that the amount of delta-v to reach other planets, over and above that to reach escape velocity can be much less if the delta-v is applied when the rocket is travelling at high speeds, close to the Earth or other planetary surface; whereas waiting until the rocket has slowed at altitude multiplies up the effort required to achieve the desired trajectory.

Safety, reliability and accidents

Space Shuttle Challenger was torn apart T+73 seconds after hot gases escaped the SRBs, causing the breakup of the Shuttle stack

See also: List of spaceflight-related accidents and incidents

The reliability of rockets, as for all physical systems, is dependent on the quality of engineering design and construction.

Because of the enormous chemical energy in rocket propellants (greater energy by weight than explosives, but lower than gasoline), consequences of accidents can be severe. Most space missions have some problems.[60] In 1986, following the Space Shuttle Challenger disaster, American physicist Richard Feynman, having served on the Rogers Commission estimated that the chance of an unsafe condition for a launch of the Shuttle was very roughly 1%;[61] more recently the historical per person-flight risk in orbital spaceflight has been calculated to be around 2%[62] or 4%.[63]

Costs and economics

The costs of rockets can be roughly divided into propellant costs, the costs of obtaining and/or producing the 'dry mass' of the rocket, and the costs of any required support equipment and facilities.[64]

Most of the takeoff mass of a rocket is normally propellant. However propellant is seldom more than a few times more expensive than gasoline per kilogram (as of 2009 gasoline was about $1/kg [$0.45/lb] or less), and although substantial amounts are needed, for all but the very cheapest rockets, it turns out that the propellant costs are usually comparatively small, although not completely negligible.[64] With liquid oxygen costing $0.15 per kilogram ($0.068/lb) and liquid hydrogen $2.20/kg ($1.00/lb), the Space Shuttle in 2009 had a liquid propellant expense of approximately $1.4 million for each launch that cost $450 million from other expenses (with 40% of the mass of propellants used by it being liquids in the external fuel tank, 60% solids in the SRBs).[65][66][67]

Even though a rocket's non-propellant, dry mass is often only between 5-20% of total mass,[68] nevertheless this cost dominates. For hardware with the performance used in orbital launch vehicles, expenses of $2000–$10,000+ per kilogram of dry weight are common, primarily from engineering, fabrication, and testing; raw materials amount to typically around 2% of total expense.[69][70] For most rockets except reusable ones (shuttle engines) the engines need not function more than a few minutes, which simplifies design.

Extreme performance requirements for rockets reaching orbit correlate with high cost, including intensive quality control to ensure reliability despite the limited safety factorsallowable for weight reasons.[70] Components produced in small numbers if not individually machined can prevent amortization of R&D and facility costs over mass production to the degree seen in more pedestrian manufacturing.[70] Amongst liquid-fueled rockets, complexity can be influenced by how much hardware must be lightweight, like pressure-fed engines can have two orders of magnitude lesser part count than pump-fed engines but lead to more weight by needing greater tank pressure, most often used in just small maneuvering thrusters as a consequence.[70]

To change the preceding factors for orbital launch vehicles, proposed methods have included mass-producing simple rockets in large quantities or on large scale,[64] or developing reusable rockets meant to fly very frequently to amortize their up-front expense over many payloads, or reducing rocket performance requirements by constructing a hypothetical non-rocket spacelaunch system for part of the velocity to orbit (or all of it but with most methods involving some rocket use).

The costs of support equipment, range costs and launch pads generally scale up with the size of the rocket, but vary less with launch rate, and so may be considered to be approximately a fixed cost.[64]

Rockets in applications other than launch to orbit (such as military rockets and rocket-assisted take off), commonly not needing comparable performance and sometimes mass-produced, are often relatively inexpensive.

See also

- ***Spaceflight portal***

Lists

- Chronology of Pakistan's rocket tests
- List of rockets
- Timeline of rocket and missile technology
- Timeline of spaceflight

General Rocketry

- Astrodynamics—the study of spaceflight trajectories
- Gantry
- Pendulum rocket fallacy—an instability of rockets
- Rocket garden—a place for viewing unlaunched rockets
- Rocket launch
- Rocket launch site
- Variable-mass system—the form of Newton's second law used for describing rocket motion

Notes

Jump up^ English *rocket*, first attested in 1566 (OED), adopted from the Italian term, given due to the similarity in shape to the bobbin or spool used to hold the thread to be fed to a spinning wheel. The modern Italian term is *razzo*.

Jump up^ The confusion is illustrated in http://science.howstuffworks.com/rocket.htm; "If you have ever seen a big fire hose spraying water, you may have noticed that it takes a lot of strength to hold the hose (sometimes you will see two or three firefighters holding the hose). The hose is acting like a rocket engine. The hose is throwing water in one direction, and the firefighters are using their strength and weight to counteract the reaction. If they were to let go of the hose, it would thrash around with tremendous force. If the firefighters were all standing on skateboards, the hose would propel them backward at great speed!"

Jump up^ "thrust-to-weight ratio F/W_g is a dimensionless parameter that is identical to the acceleration of the rocket propulsion system (expressed in multiples of g_0) ... in a gravity-free vacuum"[2]:442

Jump up^ The energy density is 31MJ per kg for aluminum and 143 MJ/kg for liquid hydrogen, this means that the vehicle consumes around 5 TJ of solid propellant and 15 TJ of hydrogen fuel

Tidal force

From Wikipedia, the free encyclopedia

(Redirected from Tidal forces)

Figure 1: Comet Shoemaker-Levy 9 in 1994 after breaking up under the influence of Jupiter's tidal forces during a previous pass in 1992.

File:Supermassive black hole rips star apart (simulation).webm

This simulation shows a star getting torn apart by the gravitational tides of a supermassive black hole.

The tidal force is an apparent force that stretches a body towards the center of mass of another body due to a gradient (difference in strength) in gravitational field from the other body; it is responsible for the diverse phenomena, including tides, tidal locking, breaking apart of celestial bodies and formation of ring systems within Roche limit, and in extreme cases, spaghettification of objects. It arises because the gravitational force exerted on one body by another is not constant across its parts: the nearest side is attracted more strongly than the farthest side. It is this difference that causes a body to get stretched. Thus, the tidal force is also known as the differential force, as well as a secondary effect of the gravitational force.

In celestial mechanics, the expression "tidal force" can refer to a situation in which a body or material (for example, tidal water) is mainly under the gravitational influence of a second body (for example, the Earth), but is also perturbed by the gravitational effects of a third body (for example, the Moon). The perturbing force is sometimes in such cases called a tidal force[1] (for example, the perturbing force on the Moon): it is the difference between the force exerted by the third body on the second and the force exerted by the third body on the first.[2

Explanation[edit]

Figure 2: The Moon's gravity *differential* field at the surface of the Earth is known (along with another and weaker differential effect due to the Sun) as the Tide Generating Force. This is the primary mechanism driving tidal action, explaining two tidal equipotentialbulges, and accounting for two high tides per day. In this figure, the Earth is the central blue circle while the Moon is far off to the right. The **outward** direction of the arrows on the right and left indicates that where the Moon is overhead (or at the nadir) its perturbing force opposes that between the earth and ocean.

When a body (body 1) is acted on by the gravity of another body (body 2), the field can vary significantly on body 1 between the side of the body facing body 2 and the side facing away from body 2. Figure 2 shows the differential force of gravity on a spherical body (body 1) exerted by another body (body 2). These so-called *tidal forces* cause strains on both bodies and may distort them or even, in extreme cases, break one or the other apart.[3] The Roche limit is the distance from a planet at which tidal effects would cause an object to disintegrate because the differential force of gravity from the planet overcomes the attraction of the parts of the object for one another.[4] These strains would not occur if the gravitational field were uniform, because a uniform field only causes the entire body to accelerate together in the same direction and at the same rate.

Effects of tidal forces [edit]

Figure 3: Saturn's rings are inside the orbits of its principal moons. Tidal forces oppose gravitational coalescence of the material in the rings to form moons.[5]

In the case of an infinitesimally small elastic sphere, the effect of a tidal force is to distort the shape of the body without any change in volume. The sphere becomes an ellipsoid with two bulges, pointing towards and away from the other body. Larger objects distort into an ovoid, and are slightly compressed, which is what happens to the Earth's oceans under the action of the Moon. The Earth and Moon rotate about their common center of mass or barycenter, and their gravitational attraction provides the centripetal force necessary to maintain this motion. To an observer on the Earth, very close to this barycenter, the situation is one of the Earth as body 1 acted upon by the gravity of the Moon as body 2. All parts of the Earth are subject to the Moon's gravitational forces, causing the water in the oceans to redistribute, forming bulges on the sides near the Moon and far from the Moon.[6]

When a body rotates while subject to tidal forces, internal friction results in the gradual dissipation of its rotational kinetic energy as heat. In the case for the Earth, and Earth's Moon, the loss of rotational kinetic energy results in a gain of about 2 milliseconds per century. If the body is close enough to its primary, this can result in a rotation which is tidally locked to the orbital motion, as in the case of the Earth's moon. Tidal heating produces dramatic volcanic effects on Jupiter's moon Io. Stresses caused by tidal forces also cause a regular monthly pattern of moonquakes on Earth's Moon.[7]

Tidal forces contribute to ocean currents, which moderate global temperatures by transporting heat energy toward the poles. It has been suggested that in addition to other factors, harmonic beat variations in tidal forcing may contribute to climate changes. However, no strong link has been found to date.[8]

Tidal effects become particularly pronounced near small bodies of high mass, such as neutron stars or black holes, where they are responsible for the "spaghettification" of infalling matter. Tidal forces create the oceanic tide of Earth's oceans, where the attracting bodies are the Moon and, to a lesser extent, the Sun. Tidal forces are also responsible for tidal locking, tidal acceleration, and tidal heating. Tides may also induce seismicity.

By generating conducting fluids within the interior of the Earth, tidal forces also affect the Earth's magnetic field.[9]

Mathematical treatment[edit]

Tidal force is responsible for the merge of galactic pair MRK 1034.[10]

Figure 4: Graphic of tidal forces. The top picture shows the gravity field of a body to the right, the lower shows their residual once the field at the centre of the sphere is subtracted; this is the tidal force. See Figure 2 for a more detailed version

For a given (externally generated) gravitational field, the **tidal acceleration** at a point with respect to a body is obtained by vectorially subtracting the gravitational acceleration at the center of the body (due to the given externally generated field) from the gravitational acceleration (due to the same field) at the given point. Correspondingly, the term ***tidal force*** is used to describe the forces due to tidal acceleration. Note that for these purposes the only gravitational field considered is the external one; the gravitational field of the body (as shown in the graphic) is not relevant. (In other words, the comparison is with the conditions at the given point as they would be if there were no externally generated field acting unequally at the given point and at the center of the reference body. The externally generated field is usually that produced by a perturbing third body, often the Sun or the Moon in the frequent example-cases of points on or above the Earth's surface in a geocentric reference frame.)

Tidal acceleration does not require rotation or orbiting bodies; for example, the body may be freefalling in a straight line under the influence of a gravitational field while still being influenced by (changing) tidal acceleration.

By Newton's law of universal gravitation and laws of motion, a body of mass *m* at distance *R* from the center of a sphere of mass *M* feels a force ,

equivalent to an acceleration ,

where is a unit vector pointing from the body *M* to the body *m* (here, acceleration from *m* towards *M* has negative sign).

Consider now the acceleration due to the sphere of mass *M* experienced by a particle in the vicinity of the body of mass *m*. With *R* as the distance from the center of *M* to the center of *m*, let Δr be the (relatively small) distance of the particle from the center of the body of mass *m*. For simplicity, distances are first considered only in the direction pointing towards or away from the sphere of mass *M*. If the body of mass *m*is itself a sphere of radius Δr, then the new particle considered may be located on its surface, at a distance ($R \pm \Delta r$) from the centre of the sphere of mass *M*, and Δr may be taken as positive where the particle's distance from *M* is greater than *R*. Leaving aside whatever gravitational acceleration may be experienced by the particle towards *m* on account of *m*'s own mass, we have the acceleration on the particle due to gravitational force towards *M* as:

Pulling out the R^2 term from the denominator gives:

The Maclaurin series of is which gives a series expansion of:

The first term is the gravitational acceleration due to *M* at the center of the

reference body , i.e., at the point where is zero. This term does not affect the observed acceleration of particles on the surface of *m* because with respect to *M*, *m* (and everything on its surface) is in free fall. When the force on the far particle is subtracted from the force on the near particle, this first term cancels, as do all other even-order terms. The remaining (residual) terms represent the difference mentioned above and are tidal force (acceleration) terms. When Δr is small compared to *R*, the terms after the first residual term are very small and can be neglected, giving the approximate tidal acceleration (axial) for the distances Δ*r*considered, along the axis joining the centers of *m* and *M*:

(axial)

When calculated in this way for the case where Δ*r* is a distance along the axis

joining the centers of *m* and *M*, is directed outwards from to the center of *m* (where Δ*r* is zero).

Tidal accelerations can also be calculated away from the axis connecting the bodies *m* and *M*, requiring a vector calculation. In the plane perpendicular to that axis, the tidal acceleration is directed inwards (towards the center where Δ*r* is

zero), and its magnitude is (axial) in linear approximation as in Figure 2.

The tidal accelerations at the surfaces of planets in the Solar System are generally very small. For example, the lunar tidal acceleration at the Earth's surface along the Moon-Earth axis is about 1.1×10^{-7} g, while the solar tidal acceleration at the Earth's surface along the Sun-Earth axis is about 0.52×10^{-7} g, where g is the gravitational acceleration at the Earth's surface. Hence the tide-raising force (acceleration) due to the Sun is about 45% of that due to the Moon.[11] The solar tidal acceleration at the Earth's surface was first given by Newton in the *Principia*.[12]]

1. **Jump up^** "On the tidal force", I. N. Avsiuk, in "Soviet Astronomy Letters", vol. 3 (1977), pp. 96–99.

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6. **Jump up^** *Rollin A Harris (1920). The Encyclopedia Americana: A Library of Universal Knowledge.* ***26****. Encyclopedia Americana Corp. pp. 611–617.*

7. **Jump up^** *"The Tidal Force | Neil deGrasse Tyson". www.haydenplanetarium.org. Retrieved 2016-10-10.*

8. **Jump up^** *"Millennial Climate Variability: Is There a Tidal Connection?".*

9. **Jump up^** *"Hungry for Power in Space". New Scienctist. New Science Pub.* ***123****: 52. 23 September 1989. Retrieved 14 March 2016.*

10. **Jump up^** *"Inseparable galactic twins". ESA/Hubble Picture of the Week. Retrieved 12 July 2013.*

11. **Jump up^** *The Admiralty (1987). Admiralty manual of navigation.* ***1****. The Stationery Office. p. 277. ISBN 0-11-772880-2.*, Chapter 11, p. 277

12. **Jump up^** *Newton, Isaac (1729). The mathematical principles of natural philosophy.* ***2****. p. 307. ISBN 0-11-772880-2.*, Book 3, Proposition 36, Page 307 Newton put the force to depress the sea at places 90 degrees distant from the Sun at "1 to 38604600" (in terms of *g*), and wrote that the force to raise the sea along the Sun-Earth axis is "twice as great", i.e. 2 to 38604600, which comes to about 0.52 × 10^{-7} *g* as expressed in the text.

External links[edit]

- Gravitational Tides by J. Christopher Mihos of Case Western Reserve University
- Audio: Cain/Gay – Astronomy Cast Tidal Forces – July 2007.

- *Gray, Meghan; Merrifield, Michael. "Tidal Forces". Sixty Symbols. Brady Haran for the University of Nottingham.*
- *"Pau Amaro Seoane MODEST working group 4 "Tidal disruption of a star by a massive black hole"". Retrieved 2013-05-30.*
- Myths about Gravity and Tides by Mikolaj Sawicki of John A. Logan College and the University of Colorado.
- Tidal Misconceptions by Donald E. Simanek

Absence of gravity[edit]

A "stationary" micro-g environment[2] would require travelling far enough into deep space so as to reduce the effect of gravity by attenuation to almost zero. This is the simplest in conception, but requires traveling an enormous distance, rendering it most impractical. For example, to reduce the gravity of the Earth by a factor of one million, one needs to be at a distance of 6 million kilometers from the Earth, but to reduce the gravity of the Sun to this amount one has to be at a distance of 3.7 billion kilometers. (The gravity due to the rest of the Milky Way is already smaller than one millionth of the gravity on Earth, so we do not need to move away further from its center[citation needed]). Thus it is not impossible, but it has only been achieved so far by four interstellar probes (Voyager 1 and 2, part of the Voyager program, Pioneer 10 and 11 part of the Pioneer program) and they did not return to Earth. To reduce the gravity to one thousandth of that on Earth's surface, one needs to be at a distance of 200,000 km.

Location	Gravity due to			Total
	Earth	Sun	rest of Milky Way	
Earth's surface	9.81 m/s^2	6 mm/s^2	200 pm/s^2 = 6 mm/s/yr	9.81 m/s^2
Low Earth orbit	9 m/s^2	6 mm/s^2	200 pm/s^2	9 m/s^2

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200,000 km from Earth	10 mm/s^2	6 mm/s^2	200 pm/s^2	up to 12 mm/s^2
6×10^6 km from Earth	10 μm/s^2	6 mm/s^2	200 pm/s^2	6 mm/s^2
3.7×10^9 km from Earth	29 pm/s^2	10 μm/s^2	200 pm/s^2	10 μm/s^2
Voyager 1 (17×10^9 km from Earth)	1 pm/s^2	500 nm/s^2	200 pm/s^2	500 nm/s^2
0.1 light-year from Earth	400 am/s^2	200 pm/s^2	200 pm/s^2	up to 400 pm/s^2

At a distance relatively close to Earth (less than 3000 km), gravity is only slightly reduced. As an object orbits a body such as the Earth, gravity is still attracting objects towards the Earth and the object is accelerated downward at almost 1g. Because the objects are typically moving laterally with respect to the surface at such immense speeds, the object will not lose altitude because of the curvature of the Earth. When viewed from an orbiting observer, other close objects in space appear to be floating because everything is being pulled towards Earth at the same speed, but also moving forward as the Earth's surface "falls" away below. All these objects are in free fall, not zero gravity.

Compare the gravitational potential at some of these locations.

Free fall[edit]

What remains is a micro-g environment moving in free fall, i.e. there are no forces other than gravity acting on the people or objects in this environment. To prevent air drag making the free fall less perfect, objects and people can free-fall in a capsule that itself, while not necessarily in free fall, is accelerated as in free fall.[citation needed] This can be done by applying a force to compensate for air drag. Alternatively free fall can be carried out in space, or in a vacuum tower or shaft.

The two cases that can be distinguished are that where the situation is only temporary because after some time the Earth's surface is or would be reached, and the case where the situation can go on indefinitely.

A temporary micro-g environment exists in a drop tube (in a tower or shaft), a sub-orbital spaceflight, e.g. with a sounding rocket, and in an airplane such as used by NASA's Reduced Gravity Research Program, aka the Vomit Comet, and by the Zero Gravity Corporation. A temporary micro-g environment is applied for training of astronauts, for some experiments, for filming movies, and for recreational purposes.

A micro-g environment for an indefinite time, while also possible in a spaceship going to infinity in a parabolic or hyperbolic orbit, is most practical in an Earth orbit. This is the environment commonly experienced in the International Space Station, Space Shuttle, etc. While this scenario is the most suitable for scientific experimentation and commercial exploitation, it is still quite expensive to operate in, mostly due to launch costs.

Tidal and inertial acceleration[edit]

Objects in orbit are not perfectly weightless due to several effects:

- Effects depending on relative position in the spacecraft:
    - Because the force of gravity decreases with distance, objects with non-zero size will be subjected to a tidal force, or a differential pull, between the ends of the object nearest and furthest from the Earth. (An extreme version of this effect is spaghettification.) At low Earth orbit (LEO) altitudes, the force differential is approximately 0.33 μ*g*/m.
    - In a spacecraft in LEO, the centrifugal force is greater on the side of the spacecraft furthest from the Earth. This is also a tidal force, adding 0.17 μ*g*/m to the first-mentioned effect.[*citation needed*]
    - "Floating" objects in a spacecraft in LEO are actually in independent orbits around the Earth. If two objects are placed side-by-side (relative

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to their direction of motion), they will be orbiting the Earth in different orbital planes. Since all orbital planes pass through the center of the earth, any two orbital planes intersect along a line. Therefore, two objects placed side-by-side (at any distance apart) will come together after one quarter of a revolution. If they are placed so they miss each other, they will oscillate past each other, with the same period as the orbit. This corresponds to an inward acceleration of 0.17 μ*g* per meter horizontal distance from the center. If they are placed one ahead of the other in the same orbital plane, they will maintain their separation. If they are placed one above the other (at different radii from the center of the Earth), they will have different potential energies, so the size, eccentricity, and period of their orbits will be different, causing them to move in a complex looping pattern relative to each other.[3]

  - Gravity between the spacecraft and an object within it may make the object slowly "fall" toward a more massive part of it. The acceleration is 0.007 μ*g* for 1000 kg at 1 m distance.

- Uniform effects (which could be compensated):

  - Though very thin, there is some air at orbital altitudes of 185 to 1,000 km. This atmosphere causes deceleration due to friction. This could be compensated by a small continuous thrust, but in practice the deceleration is only compensated from time to time, so the small g-force of this effect is not eliminated.

  - The effects of the solar wind and radiation pressure are similar, but directed away from the Sun. Unlike the effect of the atmosphere, it does not reduce with altitude.

Commercial applications[edit]

Metal spheres[edit]

In a shot tower (now obsolete), molten metal (such as lead or steel) was dripped through a sieve into free fall. With sufficient height (several hundred feet), the metal would be solid enough to resist impact (usually in a water bath) at the bottom of the tower. While the shot may have been slightly deformed by its passage through the air and by impact at the bottom, this method produced metal spheres of sufficient roundness to be used directly in shotgun shells or to be refined by further processing for applications requiring higher accuracy.

High-quality crystals[edit]

While not yet a commercial application, there has been interest in growing crystals in micro-g, as in a space station or automated artificial satellite, in an attempt to reduce crystal lattice defects.[4] Such defect-free crystals may prove useful for certain microelectronic applications and also to produce crystals for subsequent X-ray crystallography.

- 

Comparison of boiling of water under earth's gravity (1 g, left) and microgravity (right). The source of heat is in the lower part of the photograph.

- 

A comparison between the combustion of a candle on Earth (left) and in a microgravity environment, such as that found on the ISS(right).

- 

Protein crystals grown by American scientists on the Russian Space Station *Mir* in 1995.[5]

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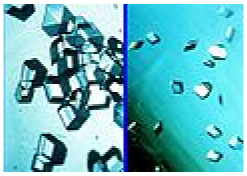
- 

Comparison of insulincrystals growth in outer space (left) and on Earth (right).

See also[edit]

- µFluids@Home — a distributed computing project that models the behavior of liquid rocket propellants in micro-g
- Weightlessness
- European Low Gravity Research Association

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2. **Jump up^** Depending on distance, "stationary" is meant relative to Earth or the Sun.
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External links[edit]

- Overview of microgravity applications and methods
- Criticism of the terms "Zero Gravity" and "Microgravity", a persuasion to use terminology that reflects accurate physics (Sci.space post).
- Space Biology Research at AU-KBC Research Centre
- Microgravity alters cancer growth and progression [1]
- The adaptation of *Escherichia coli* cells grown in simulated microgravity for an extended period is both phenotypic and genomic. [2]

Black hole

From Wikipedia, the free encyclopedia

For other uses, see Black hole (disambiguation).

A **black hole** is a region of spacetime exhibiting such strong gravitational effects that nothing—not even particles and electromagnetic radiation such as light—can escape from inside it.[1] The theory of general relativity predicts that a sufficiently compact mass can deform spacetime to form a black hole.[2][3] The boundary of the region from which no escape is possible is called the event horizon. Although the event horizon has an enormous effect on the fate and circumstances of an object crossing it, no locally detectable features appear to be observed.[4] In many ways a black hole acts like an ideal black body, as it reflects no light.[5][6] Moreover, quantum field theory in curved spacetime predicts that event horizons emit Hawking radiation, with the same spectrum as a black body of a temperature inversely proportional to its mass. This temperature is on the order of billionths of a kelvin for black holes of stellar mass, making it essentially impossible to observe.

Objects whose gravitational fields are too strong for light to escape were first considered in the 18th century by John Michell and Pierre-Simon Laplace.[7] The first modern solution of general relativity that would characterize a black hole was found by Karl Schwarzschild in 1916, although its interpretation as a region of space from which nothing can escape was first published by David Finkelstein in 1958. Black holes were long considered a mathematical curiosity; it was during the

1960s that theoretical work showed they were a generic prediction of general relativity. The discovery of neutron stars sparked interest in gravitationally collapsed compact objects as a possible astrophysical reality.

Black holes of stellar mass are expected to form when very massive stars collapse at the end of their life cycle. After a black hole has formed, it can continue to grow by absorbing mass from its surroundings. By absorbing other stars and merging with other black holes, supermassive black holes of millions of solar masses ($M_{\odot}$) may form. There is general consensus that supermassive black holes exist in the centers of most galaxies.

Despite its invisible interior, the presence of a black hole can be inferred through its interaction with other matter and with electromagnetic radiation such as visible light. Matter that falls onto a black hole can form an external accretion disk heated by friction, forming some of the brightest objects in the universe. If there are other stars orbiting a black hole, their orbits can be used to determine the black hole's mass and location. Such observations can be used to exclude possible alternatives such as neutron stars. In this way, astronomers have identified numerous stellar black hole candidates in binary systems, and established that the radio source known as Sagittarius A*, at the core of our own Milky Way galaxy, contains a supermassive black hole of about 4.3 million solar masses.

On 11 February 2016, the LIGO collaboration announced the first observation of gravitational waves; because these waves were generated from a black hole merger it was the first ever direct detection of a binary black hole merger.[8] On 15 June 2016, a second detection of a gravitational wave event from colliding black holes was announced.[9]

History

Simulated view of a black hole in front of the Large Magellanic Cloud. Note the gravitational lensing effect, which produces two enlarged but highly distorted views of the Cloud. Across the top, the Milky Way disk appears distorted into an arc.

The idea of a body so massive that even light could not escape was briefly proposed by astronomical pioneer and English clergyman John Michell in a letter published in November 1784. Michell's simplistic calculations assumed that such a body might have the same density as the Sun, and concluded that such a body would form when a star's diameter exceeds the Sun's by a factor of 500, and the surface escape velocity exceeds the usual speed of light. Michell correctly noted that such supermassive but non-radiating bodies might be detectable through their gravitational effects on nearby visible bodies.[11][7][12] Scholars of the time were initially excited by the proposal that giant but invisible stars might be hiding in plain view, but enthusiasm dampened when the wavelike nature of light became apparent in the early nineteenth century.[13] If light were a wave rather than a "corpuscle", it became unclear what, if any, influence gravity would have on escaping light waves.[7][12] Modern relativity factually dispels Michell's notion of a light ray shooting directly from the surface of a supermassive star, being slowed down by the star's gravity, stopping, and then free-falling back to the star's surface.

General relativity

In 1915, Albert Einstein developed his theory of general relativity, having earlier shown that gravity does influence light's motion. Only a few months later, Karl Schwarzschild found a solution to the Einstein field equations, which describes the gravitational field of a point mass and a spherical mass.[14] A few months after Schwarzschild, Johannes Droste, a student of Hendrik Lorentz, independently gave the same solution for the point mass and wrote more extensively about its properties.[15][16] This solution had a peculiar behaviour at what is now called the Schwarzschild radius, where it became singular, meaning that some of the terms in the Einstein equations became infinite. The nature of this surface was not quite understood at the time. In 1924, Arthur Eddington showed that the singularity disappeared after a change of coordinates (see Eddington–Finkelstein coordinates), although it took until 1933 for Georges Lemaître to realize that this meant the singularity at the Schwarzschild radius was a non-physical coordinate singularity.[17]Arthur Eddington did however comment on the possibility of a star with mass compressed to the Schwarzschild radius in a 1926 book, noting that Einstein's theory allows us to rule out overly large densities for visible stars like

Betelgeuse because "a star of 250 million km radius could not possibly have so high a density as the sun. Firstly, the force of gravitation would be so great that light would be unable to escape from it, the rays falling back to the star like a stone to the earth. Secondly, the red shift of the spectral lines would be so great that the spectrum would be shifted out of existence. Thirdly, the mass would produce so much curvature of the space-time metric that space would close up around the star, leaving us outside (i.e., nowhere)."[18][19]

In 1931, Subrahmanyan Chandrasekhar calculated, using special relativity, that a non-rotating body of electron-degenerate matter above a certain limiting mass (now called the Chandrasekhar limit at 1.4 $M_{\odot}$) has no stable solutions.[20] His arguments were opposed by many of his contemporaries like Eddington and Lev Landau, who argued that some yet unknown mechanism would stop the collapse.[21] They were partly correct: a white dwarf slightly more massive than the Chandrasekhar limit will collapse into a neutron star,[22] which is itself stable because of the Pauli exclusion principle. But in 1939, Robert Oppenheimer and others predicted that neutron stars above approximately 3 $M_{\odot}$ (the Tolman–Oppenheimer–Volkoff limit) would collapse into black holes for the reasons presented by Chandrasekhar, and concluded that no law of physics was likely to intervene and stop at least some stars from collapsing to black holes.[23]

Oppenheimer and his co-authors interpreted the singularity at the boundary of the Schwarzschild radius as indicating that this was the boundary of a bubble in which time stopped. This is a valid point of view for external observers, but not for infalling observers. Because of this property, the collapsed stars were called "frozen stars",[24] because an outside observer would see the surface of the star frozen in time at the instant where its collapse takes it inside the Schwarzschild radius.

Golden age

See also: History of general relativity

In 1958, David Finkelstein identified the Schwarzschild surface as an event horizon, "a perfect unidirectional membrane: causal influences can cross it in only one direction".[25] This did not strictly contradict Oppenheimer's results, but

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extended them to include the point of view of infalling observers. Finkelstein's solution extended the Schwarzschild solution for the future of observers falling into a black hole. A complete extension had already been found by Martin Kruskal, who was urged to publish it.[26]

These results came at the beginning of the golden age of general relativity, which was marked by general relativity and black holes becoming mainstream subjects of research. This process was helped by the discovery of pulsars in 1967,[27][28] which, by 1969, were shown to be rapidly rotating neutron stars.[29] Until that time, neutron stars, like black holes, were regarded as just theoretical curiosities; but the discovery of pulsars showed their physical relevance and spurred a further interest in all types of compact objects that might be formed by gravitational collapse.

In this period more general black hole solutions were found. In 1963, Roy Kerr found the exact solution for a rotating black hole. Two years later, Ezra Newman found the axisymmetric solution for a black hole that is both rotating and electrically charged.[30] Through the work of Werner Israel,[31] Brandon Carter,[32][33] and David Robinson[34] the no-hair theorem emerged, stating that a stationary black hole solution is completely described by the three parameters of the Kerr–Newman metric: mass, angular momentum, and electric charge.[35]

At first, it was suspected that the strange features of the black hole solutions were pathological artifacts from the symmetry conditions imposed, and that the singularities would not appear in generic situations. This view was held in particular by Vladimir Belinsky, Isaak Khalatnikov, and Evgeny Lifshitz, who tried to prove that no singularities appear in generic solutions. However, in the late 1960s Roger Penrose[36] and Stephen Hawking used global techniques to prove that singularities appear generically.[37]

Work by James Bardeen, Jacob Bekenstein, Carter, and Hawking in the early 1970s led to the formulation of black hole thermodynamics.[38] These laws describe the behaviour of a black hole in close analogy to the laws of thermodynamics by relating mass to energy, area to entropy, and surface gravity to temperature. The analogy was completed when Hawking, in 1974, showed that quantum field theory predicts that black holes should radiate like a black body with a temperature proportional to the surface gravity of the black hole.[39]

Etymology

The first use of the term "black hole" in print was by science journalist Ann Ewing in her article *"'Black Holes' in Space"*, dated 18 January 1964, which was a report on a meeting of the American Association for the Advancement of Science held in Cleveland, Ohio.[40][41]

In December 1967, a student reportedly suggested the phrase "black hole" at a lecture by John Wheeler;[40] Wheeler adopted the term for its brevity and "advertising value", and it quickly caught on,[42] leading some to credit Wheeler with coining the phrase.[43]

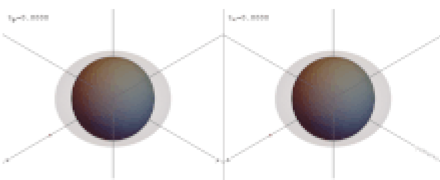
Properties and structure

A simple illustration of a non-spinning black hole

The no-hair theorem states that, once it achieves a stable condition after formation, a black hole has only three independent physical properties: mass, charge, and angular momentum.[35] Any two black holes that share the same values for these properties, or parameters, are indistinguishable according to classical (i.e. non-quantum) mechanics.

These properties are special because they are visible from outside a black hole. For example, a charged black hole repels other like charges just like any other charged object. Similarly, the total mass inside a sphere containing a black hole can be found by using the gravitational analog of Gauss's law, the ADM mass, far away from the black hole.[*clarification needed*][44] Likewise, the angular momentum can be measured from far away using frame dragging by the gravitomagnetic field.[*clarification needed*]

When an object falls into a black hole, any information about the shape of the object or distribution of charge on it is evenly distributed along the horizon of the black hole, and is lost to outside observers. The behavior of the horizon in this situation is a dissipative system that is closely analogous to that of a conductive stretchy membrane with friction and electrical resistance—the membrane paradigm.[45] This is different from other field theories such as electromagnetism, which do not have any friction or resistivity at the microscopic level, because they are time-reversible. Because a black hole eventually achieves a stable state with only three parameters, there is no way to avoid losing information about the initial conditions: the gravitational and electric fields of a black hole give very little information about what went in. The information that is lost includes every quantity that cannot be measured far away from the black hole horizon, including approximately conserved quantum numbers such as the total baryon number and lepton number. This behavior is so puzzling that it has been called the black hole information loss paradox.[46][47]



Gravitational time dilation around a black hole

Physical properties

The simplest static black holes have mass but neither electric charge nor angular momentum. These black holes are often referred to as Schwarzschild black holes after Karl Schwarzschild who discovered this solution in 1916.[14] According to Birkhoff's theorem, it is the only vacuum solution that is spherically symmetric.[48] This means that there is no observable difference between the gravitational field of such a black hole and that of any other spherical object of the same mass. The popular notion of a black hole "sucking in everything" in its surroundings is therefore only correct near a black hole's horizon; far away, the external gravitational field is identical to that of any other body of the same mass.[49]

Solutions describing more general black holes also exist. Non-rotating charged black holes are described by the Reissner–Nordström metric, while the Kerr metric describes a non-charged rotating black hole. The most

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general stationary black hole solution known is the Kerr–Newman metric, which describes a black hole with both charge and angular momentum.[50]

While the mass of a black hole can take any positive value, the charge and angular momentum are constrained by the mass. In Planck units, the total electric charge *Q* and the total angular momentum *J* are expected to satisfy

for a black hole of mass *M*. Black holes satisfying this inequality are called extremal. Solutions of Einstein's equations that violate this inequality exist, but they do not possess an event horizon. These solutions have so-called naked singularities that can be observed from the outside, and hence are deemed *unphysical*. The cosmic censorship hypothesis rules out the formation of such singularities, when they are created through the gravitational collapse of realistic matter.[2] This is supported by numerical simulations.[51]

Due to the relatively large strength of the electromagnetic force, black holes forming from the collapse of stars are expected to retain the nearly neutral charge of the star. Rotation, however, is expected to be a universal feature of compact astrophysical objects. The black-hole candidate binary X-ray source GRS 1915+105[52] appears to have an angular momentum near the maximum allowed value. That uncharged limit expressed in SI units is

Black holes are commonly classified according to their mass, independent of angular momentum *J* or electric charge *Q*. The size of a black hole, as determined by the radius of the event horizon, or Schwarzschild radius, is roughly proportional to the mass *M* through

where r_s is the Schwarzschild radius and M_{Sun} is the mass of the Sun.[55] This relation is exact only for black holes with zero charge and angular momentum; for more general black holes it can differ up to a factor of 2.

Event horizon

Main article: Event horizon

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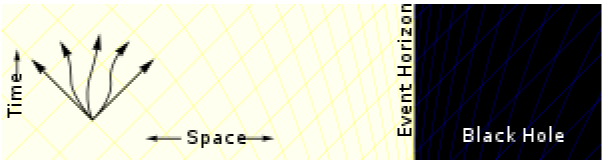
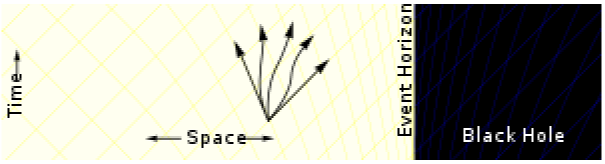
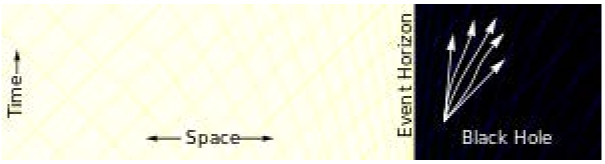


Far away from the black hole, a particle can move in any direction, as illustrated by the set of arrows. It is only restricted by the speed of light.



Closer to the black hole, spacetime starts to deform. There are more paths going towards the black hole than paths moving away.[Note 2]



Inside of the event horizon, all paths bring the particle closer to the center of the black hole. It is no longer possible for the particle to escape.

The defining feature of a black hole is the appearance of an event horizon—a boundary in spacetime through which matter and light can only pass inward towards the mass of the black hole. Nothing, not even light, can escape from inside the event horizon. The event horizon is referred to as such because if an event occurs within the boundary, information from that event cannot reach an outside observer, making it impossible to determine if such an event occurred.[57]

As predicted by general relativity, the presence of a mass deforms spacetime in such a way that the paths taken by particles bend towards the mass.[58] At the event horizon of a black hole, this deformation becomes so strong that there are no paths that lead away from the black hole.[*citation needed*]

To a distant observer, clocks near a black hole appear to tick more slowly than those further away from the black hole.[59] Due to this effect, known as gravitational time dilation, an object falling into a black hole appears to slow as

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it approaches the event horizon, taking an infinite time to reach it.[60] At the same time, all processes on this object slow down, from the view point of a fixed outside observer, causing any light emitted by the object to appear redder and dimmer, an effect known as gravitational redshift.[61] Eventually, the falling object fades away until it can no longer be seen. In reality this process happens very rapidly with an object disappearing from view within less than a second.

On the other hand, indestructible observers falling into a black hole do not notice any of these effects as they cross the event horizon. According to their own clocks, which appear to them to tick normally, they cross the event horizon after a finite time without noting any singular behaviour; it is impossible to determine the location of the event horizon from local observations.[62]

The shape of the event horizon of a black hole is always approximately spherical.[Note 3][65] For non-rotating (static) black holes the geometry of the event horizon is precisely spherical, while for rotating black holes the sphere is oblate.

Singularity

Main article: Gravitational singularity

At the center of a black hole, as described by general relativity, lies a gravitational singularity, a region where the spacetime curvature becomes infinite.[66] For a non-rotating black hole, this region takes the shape of a single point and for a rotating black hole, it is smeared out to form a ring singularity that lies in the plane of rotation.[67] In both cases, the singular region has zero volume. It can also be shown that the singular region contains all the mass of the black hole solution.[68] The singular region can thus be thought of as having infinite density.

Observers falling into a Schwarzschild black hole (*i.e.*, non-rotating and not charged) cannot avoid being carried into the singularity, once they cross the event horizon. They can prolong the experience by accelerating away to slow their descent, but only up to a limit; after attaining a certain ideal velocity, it is best to free fall the rest of the way.[69] When they reach the singularity, they are crushed to infinite density and their mass is added to the total of the black hole. Before that happens, they will have been torn apart by the growing tidal forces in a process sometimes referred to as spaghettification or the "noodle effect".[70]

In the case of a charged (Reissner–Nordström) or rotating (Kerr) black hole, it is possible to avoid the singularity. Extending these solutions as far as possible reveals the hypothetical possibility of exiting the black hole into a different spacetime with the black hole acting as a wormhole.[71] The possibility of traveling to another universe is, however, only theoretical since any perturbation would destroy this possibility.[72] It also appears to be possible to follow closed timelike curves (returning to one's own past) around the Kerr singularity, which lead to problems with causality like the grandfather paradox.[73] It is expected that none of these peculiar effects would survive in a proper quantum treatment of rotating and charged black holes.[74]

The appearance of singularities in general relativity is commonly perceived as signaling the breakdown of the theory.[75] This breakdown, however, is expected; it occurs in a situation where quantum effects should describe these actions, due to the extremely high density and therefore particle interactions. To date, it has not been possible to combine quantum and gravitational effects into a single theory, although there exist attempts to formulate such a theory of quantum gravity. It is generally expected that such a theory will not feature any singularities.[76][77]

Photon sphere

Main article: Photon sphere

The photon sphere is a spherical boundary of zero thickness in which photons that move on tangents to that sphere would be trapped in a circular orbit about the black hole. For non-rotating black holes, the photon sphere has a radius 1.5 times the Schwarzschild radius. Their orbits would be dynamically unstable, hence any small perturbation, such as a particle of infalling matter, would cause an instability that would grow over time, either setting the photon on an outward trajectory causing it to escape the black hole, or on an inward spiral where it would eventually cross the event horizon.[78]

While light can still escape from the photon sphere, any light that crosses the photon sphere on an inbound trajectory will be captured by the black hole. Hence any light that reaches an outside observer from the photon sphere must have been emitted by objects between the photon sphere and the event horizon.[78]

Other compact objects, such as neutron stars, can also have photon spheres.[79] This follows from the fact that the gravitational field *external* to a spherically-symmetric object is governed by the Schwarzschild metric, which depends only on the object's mass rather than the radius of the object, hence any object whose radius shrinks to smaller than 1.5 times the Schwarzschild radius will have a photon sphere.

Ergosphere

Main article: Ergosphere

The ergosphere is a pumpkin-shaped region outside of the event horizon, where objects cannot remain stationary.[80]

Rotating black holes are surrounded by a region of spacetime in which it is impossible to stand still, called the ergosphere. This is the result of a process known as frame-dragging; general relativity predicts that any rotating mass will tend to slightly "drag" along the spacetime immediately surrounding it. Any object near the rotating mass will tend to start moving in the direction of rotation. For a rotating black hole, this effect is so strong near the event horizon that an object would have to move faster than the speed of light in the opposite direction to just stand still.[81]

The ergosphere of a black hole is a volume whose inner boundary is the black hole's oblate spheroid event horizon and a pumpkin-shaped outer boundary,[80] which coincides with the event horizon at the poles but noticeably wider around the equator. The outer boundary is sometimes called the *ergosurface*.

Objects and radiation can escape normally from the ergosphere. Through the Penrose process, objects can emerge from the ergosphere with more energy than they entered. This energy is taken from the rotational energy of the black hole causing the latter to slow.[82]

Innermost stable circular orbit (ISCO)

Main article: Innermost stable circular orbit

In Newtonian gravity, test particles can stably orbit at arbitrary distances from a central object. In general relativity, however, there exists an innermost stable circular orbit (often called the ISCO), inside of which, any infinitesimal perturbations to a circular orbit will lead to inspiral into the black hole.[83] The location of the ISCO depends on the spin of the black hole, in the case of a Schwarzschild black hole (spin zero) is:

and decreases with increasing spin.

Formation and evolution

Considering the exotic nature of black holes, it may be natural[*clarification needed*] to question if such bizarre objects could exist in nature or to suggest that they are merely pathological solutions to Einstein's equations. Einstein himself wrongly thought that black holes would not form, because he held that the angular momentum of collapsing particles would stabilize their motion at some radius.[84] This led the general relativity community to dismiss all results to the contrary for many years. However, a minority of relativists continued to contend that black holes were physical objects,[85] and by the end of the 1960s, they had persuaded the majority of researchers in the field that there is no obstacle to the formation of an event horizon.

Two Black Holes Colliding

Penrose proved that once an event horizon forms, general relativity without quantum mechanics requires that a singularity will form within.[36]Shortly afterwards, Hawking showed that many cosmological solutions that describe the Big Bang have singularities without scalar fields or other exotic matter (see "Penrose–Hawking singularity theorems").[*clarification needed*] The Kerr solution, the no-hair theorem, and the laws of black hole thermodynamics showed that the physical properties of black holes were simple and comprehensible, making them respectable subjects for research.[86] The primary formation process for black holes is expected to be the gravitational collapse of heavy objects such as stars, but there are also more exotic processes that can lead to the production of black holes.

Gravitational collapse

Main article: Gravitational collapse

Gravitational collapse occurs when an object's internal pressure is insufficient to resist the object's own gravity. For stars this usually occurs either because a star has too little "fuel" left to maintain its temperature through stellar nucleosynthesis, or because a star that would have been stable receives extra matter in a way that does not raise its core temperature. In either case the star's temperature is no longer high enough to prevent it from collapsing under its own weight.[87] The collapse may be stopped by the degeneracy pressure of the star's constituents, allowing the condensation of matter into an exotic denser state. The result is one of the various types of compact star. The type of compact star formed depends on the mass of the remnant of the original star left after the outer layers have been blown away. Such explosions and pulsations lead to planetary nebula.[88] This mass can be substantially less than the original star. Remnants exceeding 5 $M_\odot$ are produced by stars that were over 20 $M_\odot$ before the collapse.[87]

If the mass of the remnant exceeds about 3–4 $M_\odot$ (the Tolman–Oppenheimer–Volkoff limit[23]), either because the original star was very heavy or because the remnant collected additional mass through accretion of matter, even the degeneracy pressure of neutrons is insufficient to stop the collapse. No known mechanism (except possibly quark degeneracy pressure, see quark star) is powerful enough to stop the implosion and the object will inevitably collapse to form a black hole.[87]

Artist’s impression of supermassive black hole seed.[89]

The gravitational collapse of heavy stars is assumed to be responsible for the formation of stellar mass black holes. Star formation in the early universe may have resulted in very massive stars, which upon their collapse would have produced black holes of up to 10^3 $M_\odot$. These black holes could be the seeds of the supermassive black holes found in the centers of most galaxies.[90] It has further

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been suggested that supermassive black holes with typical masses of ~10^5 $M_\odot$ could have formed from the direct collapse of gas clouds in the young universe.[91]Some candidates for such objects have been found in observations of the young universe.[91]

While most of the energy released during gravitational collapse is emitted very quickly, an outside observer does not actually see the end of this process. Even though the collapse takes a finite amount of time from the reference frame of infalling matter, a distant observer would see the infalling material slow and halt just above the event horizon, due to gravitational time dilation. Light from the collapsing material takes longer and longer to reach the observer, with the light emitted just before the event horizon forms delayed an infinite amount of time. Thus the external observer never sees the formation of the event horizon; instead, the collapsing material seems to become dimmer and increasingly red-shifted, eventually fading away.[92]

Primordial black holes and the Big Bang

Gravitational collapse requires great density. In the current epoch of the universe these high densities are only found in stars, but in the early universe shortly after the big bangdensities were much greater, possibly allowing for the creation of black holes. The high density alone is not enough to allow the formation of black holes since a uniform mass distribution will not allow the mass to bunch up. In order for primordial black holes to form in such a dense medium, there must be initial density perturbations that can then grow under their own gravity. Different models for the early universe vary widely in their predictions of the size of these perturbations. Various models predict the creation of black holes, ranging from a Planck mass to hundreds of thousands of solar masses.[93] Primordial black holes could thus account for the creation of any type of black hole.[*clarification needed*]

Despite the early universe being extremely dense—far denser than is usually required to form a black hole—it did not re-collapse into a black hole during the big bang. This is because currently-known calculations and density limits for gravitational collapse are usually based upon objects of relatively constant size,

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such as stars, and do not necessarily apply in the same way to rapidly expanding space such as the Big Bang.[*citation needed*]

High-energy collisions

A simulated event in the CMS detector, a collision in which a micro black hole may be created.

Gravitational collapse is not the only process that could create black holes. In principle, black holes could be formed in high-energy collisions that achieve sufficient density. As of 2002, no such events have been detected, either directly or indirectly as a deficiency of the mass balance in particle accelerator experiments.[94] This suggests that there must be a lower limit for the mass of black holes. Theoretically, this boundary is expected to lie around the Planck mass ($m_P = \sqrt{\hbar c/G} \approx 1.2\times10^{19}$ GeV/c^2 $\approx 2.2\times10^{-8}$ kg), where quantum effects are expected to invalidate the predictions of general relativity.[95] This would put the creation of black holes firmly out of reach of any high-energy process occurring on or near the Earth. However, certain developments in quantum gravity suggest that the Planck mass could be much lower: some braneworld scenarios for example put the boundary as low as 1 TeV/c^2.[96] This would make it conceivable for micro black holes to be created in the high-energy collisions that occur when cosmic rays hit the Earth's atmosphere, or possibly in the Large Hadron Collider at CERN. These theories are very speculative, and the creation of black holes in these processes is deemed unlikely by many specialists.[97]Even if micro black holes could be formed, it is expected that they would evaporate in about 10^{-25} seconds, posing no threat to the Earth.[98]

Growth

Once a black hole has formed, it can continue to grow by absorbing additional matter. Any black hole will continually absorb gas and interstellar dust from its surroundings and omnipresent cosmic background radiation. This is the primary process through which supermassive black holes seem to have grown.[90] A similar process has been suggested for the formation of intermediate-mass black holes found in globular clusters.[99]

Another possibility for black hole growth, is for a black hole to merge with other objects such as stars or even other black holes. Although not necessary for growth, this is thought to have been important, especially for the early development of supermassive black holes, which could have formed from the coagulation of many smaller objects.[90] The process has also been proposed as the origin of some intermediate-mass black holes.[100][101]

Evaporation

Main article: Hawking radiation

In 1974, Hawking predicted that black holes are not entirely black but emit small amounts of thermal radiation;[39] this effect has become known as Hawking radiation. By applying quantum field theory to a static black hole background, he determined that a black hole should emit particles that display a perfect black body spectrum. Since Hawking's publication, many others have verified the result through various approaches.[102] If Hawking's theory of black hole radiation is correct, then black holes are expected to shrink and evaporate over time as they lose mass by the emission of photons and other particles.[39] The temperature of this thermal spectrum (Hawking temperature) is proportional to the surface gravityof the black hole, which, for a Schwarzschild black hole, is inversely proportional to the mass. Hence, large black holes emit less radiation than small black holes.[103]

A stellar black hole of 1 $M_\odot$ has a Hawking temperature of about 100 nanokelvins. This is far less than the 2.7 K temperature of the cosmic microwave background radiation. Stellar-mass or larger black holes receive more mass from the cosmic microwave background than they emit through Hawking radiation and thus will grow instead of shrink.[*citation needed*] To have a Hawking temperature larger than 2.7 K (and be able to evaporate), a black hole would need a mass less than the Moon. Such a black hole would have a diameter of less than a tenth of a millimeter.[104]

If a black hole is very small, the radiation effects are expected to become very strong. Even a black hole that is heavy compared to a human would evaporate in an instant. A black hole with the mass of a car would have a diameter of about

10^{-24} m and take a nanosecond to evaporate, during which time it would briefly have a luminosity of more than 200 times that of the Sun. Lower-mass black holes are expected to evaporate even faster; for example, a black hole of mass 1 TeV/c^2 would take less than 10^{-88} seconds to evaporate completely. For such a small black hole, quantum gravitation effects are expected to play an important role and could hypothetically make such a small black hole stable, although current developments in quantum gravity do not indicate so.[105][106]

The Hawking radiation for an astrophysical black hole is predicted to be very weak and would thus be exceedingly difficult to detect from Earth. A possible exception, however, is the burst of gamma rays emitted in the last stage of the evaporation of primordial black holes. Searches for such flashes have proven unsuccessful and provide stringent limits on the possibility of existence of low mass primordial black holes.[107] NASA's Fermi Gamma-ray Space Telescope launched in 2008 will continue the search for these flashes.[108]

Observational evidence

Predicted appearance of non-rotating black hole with toroidal ring of ionised matter, such as has been proposed[109] as a model for Sagittarius A*. The asymmetry is due to the Doppler effect resulting from the enormous orbital speed needed for centrifugal balance of the very strong gravitational attraction of the hole.

By their very nature, black holes do not directly emit any electromagnetic radiation other than the hypothetical Hawking radiation, so astrophysicists searching for black holes must generally rely on indirect observations. For example, a black hole's existence can sometimes be inferred by observing its gravitational interactions with its surroundings.

The Event Horizon Telescope (EHT), however, run by MIT's Haystack Observatory, is an attempt to directly observe the immediate environment of the event horizon of Sagittarius A*, the black hole at the centre of the Milky Way, and to produce a silhouetted image of it. The first such image may appear as early as 2018.[110] In 2015, the EHT managed to detect magnetic fields just outside the event horizon of Sagittarius A*, and even discern some of their properties. The

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existence of magnetic fields had been predicted by theoretical studies of black holes.[111][112]

Detection of gravitational waves from merging black holes

On 14 September 2015 the LIGO gravitational wave observatory made the first-ever successful observation of gravitational waves.[8][113] The signal was consistent with theoretical predictions for the gravitational waves produced by the merger of two black holes: one with about 36 solar masses, and the other around 29 solar masses.[8][114] This observation provides the most concrete evidence for the existence of black holes to date. For instance, the gravitational wave signal suggests that the separation of the two objects prior to the merger was just 350 km (or roughly 4 times the Schwarzschild radius corresponding to the inferred masses). The objects must therefore have been extremely compact, leaving black holes as the most plausible interpretation.[8]

More importantly, the signal observed by LIGO also included the start of the post-merger ringdown, the signal produced as the newly formed compact object settles down to a stationary state. Arguably, the ringdown is the most direct way of observing a black hole.[115] From the LIGO signal it is possible to extract the frequency and damping time of the dominant mode of the ringdown. From these it is possible to infer the mass and angular momentum of the final object, which match independent predictions from numerical simulations of the merger.[116] The frequency and decay time of the dominant mode are determined by the geometry of the photon sphere. Hence, observation of this mode confirms the presence of a photon sphere, however it cannot exclude possible exotic alternatives to black holes that are compact enough to have a photon sphere.[115]

The observation also provides the first observational evidence for the existence of stellar-mass black hole binaries. Furthermore, it is the first observational evidence of stellar-mass black holes weighing 25 solar masses or more.[117]

Proper motions of stars orbiting Sagittarius A*

The proper motions of stars near the center of our own Milky Way provide strong observational evidence that these stars are orbiting a supermassive black hole.[118] Since 1995, astronomers have tracked the motions of 90 stars orbiting an invisible object coincident with the radio source Sagittarius A*. By fitting their motions to Keplerian orbits, the astronomers were able to infer, in 1998, that a 2.6 million $M_{\odot}$ object must be contained in a volume with a radius of 0.02 light-years to cause the motions of those stars.[119] Since then, one of the stars—called S2—has completed a full orbit. From the orbital data, astronomers were able to refine the calculations of the mass to 4.3 million $M_{\odot}$ and a radius of less than 0.002 light years for the object causing the orbital motion of those stars.[118] The upper limit on the object's size is still too large to test whether it is smaller than its Schwarzschild radius; nevertheless, these observations strongly suggest that the central object is a supermassive black hole as there are no other plausible scenarios for confining so much invisible mass into such a small volume.[119] Additionally, there is some observational evidence that this object might possess an event horizon, a feature unique to black holes.[120]

Accretion of matter

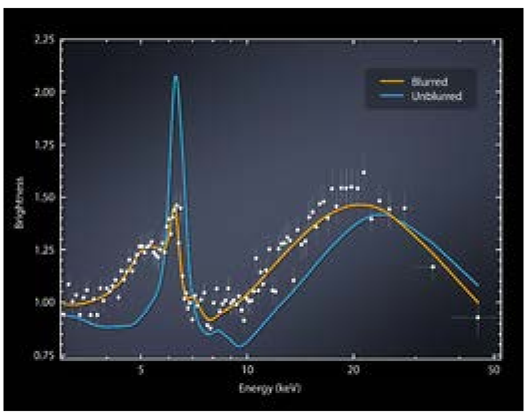
See also: Accretion disc

Black hole with corona, X-ray source (artist's concept).[121]

Due to conservation of angular momentum, gas falling into the gravitational well created by a massive object will typically form a disc-like structure around the object. Artists' impressions such as the accompanying representation of a black hole with corona commonly depict the black hole as if it were a flat-space material body hiding the part of the disc just behind it, but detailed mathematical modelling[122] shows that the image of the disc would actually be distorted by the bending of light that originated behind the black hole in such a way that the upper side of the disc would be entirely visible, while there would be a partially visible secondary image of the underside of the disk.

Predicted view from outside the horizon of a Schwarzschild black hole lit by a thin accretion disc

Within such a disc, friction would cause angular momentum to be transported outward, allowing matter to fall further inward, thus releasing potential energy and increasing the temperature of the gas.[123]



Blurring of X-rays near black hole (NuSTAR; 12 August 2014).[121]

When the accreting object is a neutron star or a black hole, the gas in the inner accretion disc orbits at very high speeds because of its proximity to the compact object. The resulting friction is so significant that it heats the inner disc to temperatures at which it emits vast amounts of electromagnetic radiation (mainly X-rays). These bright X-ray sources may be detected by telescopes. This process of accretion is one of the most efficient energy-producing processes known; up to 40% of the rest mass of the accreted material can be emitted as radiation.[123](In nuclear fusion only about 0.7% of the rest mass will be emitted as energy.) In many cases, accretion discs are accompanied by relativistic jets that are emitted

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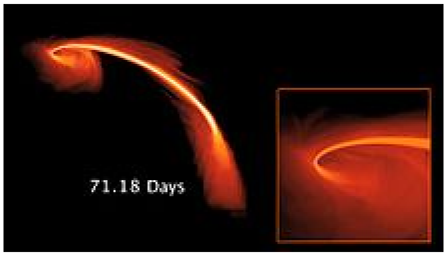
along the poles, which carry away much of the energy. The mechanism for the creation of these jets is currently not well understood.

As such, many of the universe's more energetic phenomena have been attributed to the accretion of matter on black holes. In particular, active galactic nuclei and quasars are believed to be the accretion discs of supermassive black holes.[124] Similarly, X-ray binaries are generally accepted to be binary star systems in which one of the two stars is a compact object accreting matter from its companion.[124] It has also been suggested that some ultraluminous X-ray sources may be the accretion disks of intermediate-mass black holes.[125]

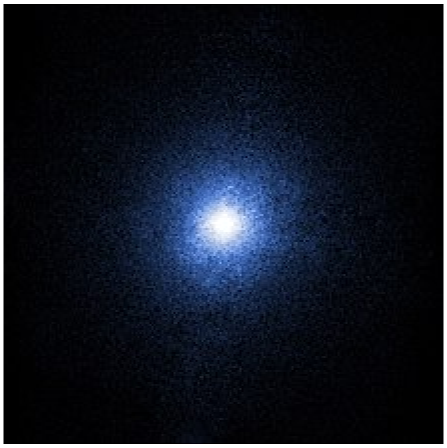
In November 2011 the first direct observation of a quasar accretion disk around a supermassive black hole was reported.[126][127]

X-ray binaries

See also: X-ray binary



A computer simulation of a star being consumed by a black hole. The blue dot indicates the location of the black hole.



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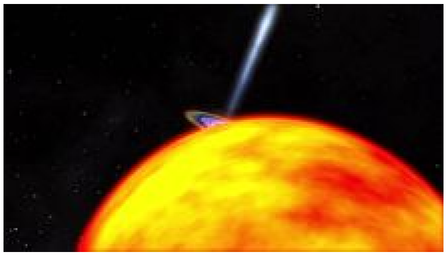
A Chandra X-Ray Observatoryimage of Cygnus X-1, which was the first strong black hole candidate discovered

X-ray binaries are binary star systems that emit a majority of their radiation in the X-ray part of the spectrum. These X-ray emissions are generally thought to result when one of the stars (compact object) accretes matter from another (regular) star. The presence of an ordinary star in such a system provides a unique opportunity for studying the central object and to determine if it might be a black hole.



This animation compares the X-ray 'heartbeats' of GRS 1915 and IGR J17091, two black holes that ingest gas from companion stars.

If such a system emits signals that can be directly traced back to the compact object, it cannot be a black hole. The absence of such a signal does, however, not exclude the possibility that the compact object is a neutron star. By studying the companion star it is often possible to obtain the orbital parameters of the system and to obtain an estimate for the mass of the compact object. If this is much larger than the Tolman–Oppenheimer–Volkoff limit (that is, the maximum mass a neutron star can have before it collapses) then the object cannot be a neutron star and is generally expected to be a black hole.[124]

The first strong candidate for a black hole, Cygnus X-1, was discovered in this way by Charles Thomas Bolton,[128] Louise Webster and Paul Murdin[129] in 1972.[130][131] Some doubt, however, remained due to the uncertainties that result from the companion star being much heavier than the candidate black hole.[124] Currently, better candidates for black holes are found in a class of X-ray binaries called soft X-ray transients.[124] In this class of system, the companion star is of relatively low mass allowing for more accurate estimates of the black hole mass. Moreover, these systems are actively emit X-rays for only several months once every 10–50 years. During the period of low X-ray emission (called quiescence), the accretion disc is extremely faint allowing detailed observation of the companion star during this period. One of the best such candidates is V404 Cyg.

Quiescence and advection-dominated accretion flow

The faintness of the accretion disc of an X-ray binary during quiescence is suspected to be caused by the flow of mass entering a mode called an advection-dominated accretion flow (ADAF). In this mode, almost all the energy generated by friction in the disc is swept along with the flow instead of radiated away. If this model is correct, then it forms strong qualitative evidence for the presence of an event horizon,[132] since if the object at the center of the disc had a solid surface, it would emit large amounts of radiation as the highly energetic gas hits the surface,[*clarification needed*] an effect that is observed for neutron stars in a similar state.[123]

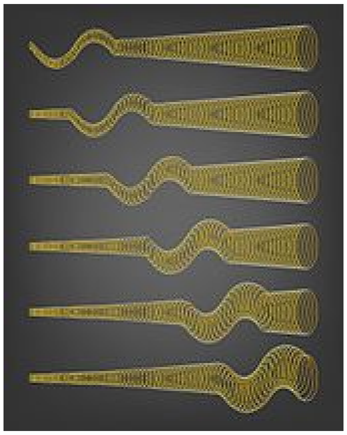
Quasi-periodic oscillations

Main article: Quasi-periodic oscillations

The X-ray emissions from accretion disks sometimes flicker at certain frequencies. These signals are called quasi-periodic oscillations and are thought to be caused by material moving along the inner edge of the accretion disk (the innermost stable circular orbit). As such their frequency is linked to the mass of the compact object. They can thus be used as an alternative way to determine the mass of candidate black holes.[133]

Galactic nuclei

See also: Active galactic nucleus



Magnetic waves, called Alfvén S-waves, flow from the base of black hole jets.

Astronomers use the term "active galaxy" to describe galaxies with unusual characteristics, such as unusual spectral line emission and very strong radio emission. Theoretical and observational studies have shown that the activity in these active galactic nuclei (AGN) may be explained by the presence of supermassive black holes, which can be millions of times more massive than stellar ones. The models of these AGN consist of a central black hole that may be millions or billions of times more massive than the Sun; a disk of gas and dust called an accretion disk; and two jetsperpendicular to the accretion disk.[134][135]

Detection of unusually bright X-Rayflare from Sagittarius A*, a black hole in the center of the Milky Way galaxyon 5 January 2015.[136]

Although supermassive black holes are expected to be found in most AGN, only some galaxies' nuclei have been more carefully studied in attempts to both identify and measure the actual masses of the central supermassive black hole candidates. Some of the most notable galaxies with supermassive black hole candidates include the Andromeda Galaxy, M32, M87, NGC 3115, NGC 3377, NGC 4258, NGC 4889, NGC 1277, OJ 287, APM 08279+5255 and the Sombrero Galaxy.[137]

It is now widely accepted that the center of nearly every galaxy, not just active ones, contains a supermassive black hole.[138] The close observational correlation between the mass of this hole and the velocity dispersion of the host galaxy's bulge, known as the M-sigma relation, strongly suggests a connection between the formation of the black hole and the galaxy itself.[139]

Simulation of gas cloud after close approach to the black hole at the centre of the Milky Way.[140]

Microlensing (proposed)

Another way that the black hole nature of an object may be tested in the future is through observation of effects caused by a strong gravitational field in their vicinity. One such effect is gravitational lensing: The deformation of spacetime around a massive object causes light rays to be deflected much as light passing through an optic lens. Observations have been made of weak gravitational lensing, in which light rays are deflected by only a few arcseconds. However, it has never been directly observed for a black hole.[141] One possibility for observing gravitational lensing by a black hole would be to observe stars in orbit around the black hole. There are several candidates for such an observation in orbit around Sagittarius A*.[141]

Alternatives

See also: Exotic star

The evidence for stellar black holes strongly relies on the existence of an upper limit for the mass of a neutron star. The size of this limit heavily depends on the assumptions made about the properties of dense matter. New exotic phases of matter could push up this bound.[124]A phase of free quarks at high density might allow the existence of dense quark stars,[142] and some supersymmetric models predict the existence of Q stars.[143] Some extensions of the standard model posit the existence of preons as fundamental building blocks of quarks and leptons, which could hypothetically form preon stars.[144] These hypothetical models could potentially explain a number of observations of stellar black hole candidates. However, it can be shown from arguments in general relativity that any such object will have a maximum mass.[124]

Since the average density of a black hole inside its Schwarzschild radius is inversely proportional to the square of its mass, supermassive black holes are much less dense than stellar black holes (the average density of a 10^8 $M_\odot$ black hole is comparable to that of water).[124] Consequently, the physics of matter forming a supermassive black hole is much better understood and the possible alternative explanations for supermassive black hole observations are much more mundane. For example, a supermassive black hole could be modelled by a large cluster of very dark objects. However, such alternatives are typically not stable enough to explain the supermassive black hole candidates.[124]

The evidence for the existence of stellar and supermassive black holes implies that in order for black holes to not form, general relativity must fail as a theory of gravity, perhaps due to the onset of quantum mechanical corrections. A much anticipated feature of a theory of quantum gravity is that it will not feature singularities or event horizons and thus black holes would not be real artifacts.[145] In 2002,[146] much attention has been drawn by the fuzzball model in string theory. Based on calculations for specific situations in string theory, the proposal suggests that generically the individual states of a black hole solution do not have an event horizon or singularity, but that for a classical/semi-classical observer the statistical average of such states appears just as an ordinary black hole as deduced from general relativity.[147]

There are a few theoretical objects which would match observations of astronomical black hole candidates identically or near-identically, but which function via a different mechanism. These include the gravastar, the dark-energy star, and the black star (semiclassical gravity).

Open questions

Entropy and thermodynamics

Further information: Black hole thermodynamics

$$S = \frac{1}{4}\frac{c^3 k}{G\hbar}A$$

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The formula for the Bekenstein–Hawking entropy (S) of a black hole, which depends on the area of the black hole (A). The constants are the speed of light (c), the Boltzmann constant (k), Newton's constant (G), and the reduced Planck constant (ħ).

In 1971, Hawking showed under general conditions[Note 4] that the total area of the event horizons of any collection of classical black holes can never decrease, even if they collide and merge.[148] This result, now known as the second law of black hole mechanics, is remarkably similar to the second law of thermodynamics, which states that the total entropy of a system can never decrease. As with classical objects at absolute zero temperature, it was assumed that black holes had zero entropy. If this were the case, the second law of thermodynamics would be violated by entropy-laden matter entering a black hole, resulting in a decrease of the total entropy of the universe. Therefore, Bekenstein proposed that a black hole should have an entropy, and that it should be proportional to its horizon area.[149]

The link with the laws of thermodynamics was further strengthened by Hawking's discovery that quantum field theory predicts that a black hole radiates blackbody radiation at a constant temperature. This seemingly causes a violation of the second law of black hole mechanics, since the radiation will carry away energy from the black hole causing it to shrink. The radiation, however also carries away entropy, and it can be proven under general assumptions that the sum of the entropy of the matter surrounding a black hole and one quarter of the area of the horizon as measured in Planck units is in fact always increasing. This allows the formulation of the first law of black hole mechanics as an analogue of the first law of thermodynamics, with the mass acting as energy, the surface gravity as temperature and the area as entropy.[149]

One puzzling feature is that the entropy of a black hole scales with its area rather than with its volume, since entropy is normally an extensive quantity that scales linearly with the volume of the system. This odd property led Gerard 't Hooft and Leonard Susskind to propose the holographic principle, which suggests that anything that happens in a volume of spacetime can be described by data on the boundary of that volume.[150]

Although general relativity can be used to perform a semi-classical calculation of black hole entropy, this situation is theoretically unsatisfying. In statistical mechanics, entropy is understood as counting the number of microscopic configurations of a system that have the same macroscopic qualities (such as mass, charge, pressure, etc.). Without a satisfactory theory of quantum gravity, one cannot perform such a computation for black holes. Some progress has been made in various approaches to quantum gravity. In 1995, Andrew Strominger and Cumrun Vafa showed that counting the microstates of a specific supersymmetric black hole in string theory reproduced the Bekenstein–Hawking entropy.[151]Since then, similar results have been reported for different black holes both in string theory and in other approaches to quantum gravity like loop quantum gravity.[152]

Information loss paradox

Main article: Black hole information paradox

Because a black hole has only a few internal parameters, most of the information about the matter that went into forming the black hole is lost. Regardless of the type of matter which goes into a black hole, it appears that only information concerning the total mass, charge, and angular momentum are conserved. As long as black holes were thought to persist forever this information loss is not that problematic, as the information can be thought of as existing inside the black hole, inaccessible from the outside. However, black holes slowly evaporate by emitting Hawking radiation. This radiation does not appear to carry any additional information about the matter that formed the black hole, meaning that this information appears to be gone forever.[153]

The question whether information is truly lost in black holes (the black hole information paradox) has divided the theoretical physics community (see Thorne–Hawking–Preskill bet). In quantum mechanics, loss of information corresponds to the violation of vital property called unitarity, which has to do with the conservation of probability. It has been argued that loss of unitarity would also imply violation of conservation of energy.[154] Over recent years evidence has been building that indeed information and unitarity are preserved in a full quantum gravitational treatment of the problem.[155]

The firewall paradox

Main article: Firewall (physics)

According to quantum field theory in curved spacetime, a single emission of Hawking radiation involves two mutually entangled particles. The outgoing particle escapes and is emitted as a quantum of Hawking radiation; the infalling particle is swallowed by the black hole. Assume a black hole formed a finite time in the past and will fully evaporate away in some finite time in the future. Then, it will only emit a finite amount of information encoded within its

Hawking radiation. Assume that at time , more than half of the information had already been emitted. According to widely accepted research by physicists like Don Page[156][157] and Leonard Susskind, an outgoing particle emitted at

time must be entangled with all the Hawking radiation the black hole has previously emitted. This creates a paradox: a principle called "monogamy of entanglement" requires that, like any quantum system, the outgoing particle cannot be fully entangled with two independent systems at the same time; yet here the outgoing particle appears to be entangled with both the infalling particle and, independently, with past Hawking radiation.[158]

In order to resolve the paradox, physicists may eventually be forced to give up one of three time-tested theories: Einstein's equivalence principle, unitarity, or existing quantum field theory. One possible solution, which violates the equivalence principle, is that a "firewall" destroys incoming particles at the event horizon.[159] A 2016 analysis of LIGO data shows tentative signs of echoes caused by a fuzzy event horizon; such echoes may be possible in firewall or fuzzball theories but should not occur in classical general relativity. Over the next two years, additional LIGO data should establish whether the echoes were just random noise, or whether they are instead evidence of a violation of classical general relativity.[160]

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See alsoAn **inertial frame of reference**, in classical physics, is a frame of reference in which bodies, whose net force acting upon them is zero, are not accelerated, that is they are at rest or they move at a constant velocity in a straight line.[1] In analytical terms, it is a frame of reference that describes time and space homogeneously, isotropically, and in a time-independent manner.[2] Conceptually, in classical physics and special relativity, the physics of a system in an inertial frame have no causes external to the system.[3] An inertial frame of reference may also be called an **inertial reference frame**, **inertial frame**, **Galilean reference frame**, or **inertial space**.[*citation needed*]

All inertial frames are in a state of constant, rectilinear motion with respect to one another; an accelerometer moving with any of them would detect zero acceleration. Measurements in one inertial frame can be converted to measurements in another by a simple transformation (the Galilean transformation in Newtonian physics and the Lorentz transformation in special relativity). In general relativity, in any region small enough for the curvature of spacetime and tidal forces[4] to be negligible, one can find a set of inertial frames that approximately describe that region.[5][6]

In a non-inertial reference frame in classical physics and special relativity, the physics of a system vary depending on the acceleration of that frame with respect to an inertial frame, and the usual physical forces must be supplemented by fictitious forces.[7][8] In contrast, systems in non-inertial frames in general relativity don't have external causes, because of the principle of geodesic motion.[9] In classical physics, for example, a ball dropped towards the ground does not go exactly straight down because the Earth is rotating, which means the frame of reference of an observer on Earth is not inertial. The physics must account for the Coriolis effect—in this case thought of as a force—to predict the horizontal motion. Another example of such a fictitious force associated with rotating reference frames is the centrifugal effect, or centrifugal force.

Introduction[edit]

The motion of a body can only be described relative to something else—other bodies, observers, or a set of space-time coordinates. These are called frames of reference. If the coordinates are chosen badly, the laws of motion may be more complex than necessary. For example, suppose a free body that has no external forces acting on it is at rest at some instant. In many coordinate systems, it would begin to move at the next instant, even though there are no forces on it. However, a frame of reference can always be chosen in which it remains stationary. Similarly, if space is not described uniformly or time independently, a coordinate system could describe the simple flight of a free body in space as a complicated zig-zag in its coordinate system. Indeed, an intuitive summary of inertial frames can be given as: In an inertial reference frame, the laws of mechanics take their simplest form.[2]

In an inertial frame, Newton's first law, the *law of inertia*, is satisfied: Any free motion has a constant magnitude and direction.[2] Newton's second law for a particle takes the form:

with **F** the net force (a vector), *m* the mass of a particle and **a** the acceleration of the particle (also a vector) which would be measured by an observer at rest in the frame. The force **F**is the vector sum of all "real" forces on the particle, such as electromagnetic, gravitational, nuclear and so forth. In contrast, Newton's second law in a rotating frame of reference, rotating at angular rate Ω about an axis, takes the form:

which looks the same as in an inertial frame, but now the force **F′** is the resultant of not only **F**, but also additional terms (the paragraph following this equation presents the main points without detailed mathematics):

where the angular rotation of the frame is expressed by the vector **Ω** pointing in the direction of the axis of rotation, and with magnitude equal to the angular rate of rotation Ω, symbol × denotes the vector cross product, vector $\mathbf{x}_B$ locates the body and vector $\mathbf{v}_B$ is the velocity of the body according to a rotating observer (different from the velocity seen by the inertial observer).

The extra terms in the force **F′** are the "fictitious" forces for this frame, whose causes are external to the system in the frame. The first extra term is the Coriolis force, the second the centrifugal force, and the third the Euler force. These terms all have these properties: they vanish when $\Omega = 0$; that is, they are zero for an inertial frame (which, of course, does not rotate); they take on a different magnitude and direction in every rotating frame, depending upon its particular value of **Ω**; they are ubiquitous in the rotating frame (affect every particle, regardless of circumstance); and they have no apparent source in identifiable physical sources, in particular, matter. Also, fictitious forces do not drop off with distance (unlike, for example, nuclear forces or electrical forces). For example, the centrifugal force that appears to emanate from the axis of rotation in a rotating frame increases with distance from the axis.

All observers agree on the real forces, **F**; only non-inertial observers need fictitious forces. The laws of physics in the inertial frame are simpler because unnecessary forces are not present.

In Newton's time the fixed stars were invoked as a reference frame, supposedly at rest relative to absolute space. In reference frames that were either at rest with respect to the fixed stars or in uniform translation relative to these stars, Newton's laws of motion were supposed to hold. In contrast, in frames accelerating with respect to the fixed stars, an important case being frames rotating relative to the fixed stars, the laws of motion did not hold in their simplest form, but had to be supplemented by the addition of fictitious forces, for example, the Coriolis force and the centrifugal force. Two interesting experiments were devised by Newton to demonstrate how these forces could be discovered, thereby revealing to an observer that they were not in an inertial frame: the example of the tension in the cord linking two spheres rotating about their center of gravity, and the example of the curvature of the surface of water in a rotating bucket. In both cases, application of Newton's second law would not work for the rotating observer without invoking centrifugal and Coriolis forces to account for their observations (tension in the case of the spheres; parabolic water surface in the case of the rotating bucket).

As we now know, the fixed stars are not fixed. Those that reside in the Milky Way turn with the galaxy, exhibiting proper motions. Those that are outside our galaxy (such as nebulae once mistaken to be stars) participate in their own motion as well, partly due to expansion of the universe, and partly due to peculiar velocities.[10] The Andromeda galaxy is on collision course with the Milky Way at a speed of 117 km/s.[11] The concept of inertial frames of reference is no longer tied to either the fixed stars or to absolute space. Rather, the identification of an inertial frame is based upon the simplicity of the laws of physics in the frame. In particular, the absence of fictitious forces is their identifying property.[12]

In practice, although not a requirement, using a frame of reference based upon the fixed stars as though it were an inertial frame of reference introduces very little discrepancy. For example, the centrifugal acceleration of the Earth because of its rotation about the Sun is about thirty million times greater than that of the Sun about the galactic center.[13]

To illustrate further, consider the question: "Does our Universe rotate?" To answer, we might attempt to explain the shape of the Milky Way galaxy using the laws of physics,[14] although other observations might be more definitive, that is, provide larger discrepancies or less measurement uncertainty, like the anisotropy of the microwave background radiation or Big Bang nucleosynthesis.[15][16] The flatness of the Milky Way depends on its rate of rotation in an inertial frame of reference. If we attribute its apparent rate of rotation entirely to rotation in an inertial frame, a different "flatness" is predicted than if we suppose part of this rotation actually is due to rotation of the universe and should not be included in the rotation of the galaxy itself. Based upon the laws of physics, a model is set up in which one parameter is the rate of rotation of the Universe. If the laws of physics agree more accurately with observations in a model with rotation than without it, we are inclined to select the best-fit value for rotation, subject to all other pertinent experimental observations. If no value of the rotation parameter is successful and theory is not within observational error, a modification of physical law is considered, for example, dark matter is invoked to explain the galactic rotation curve. So far, observations show any rotation of the universe is very slow, no faster than once every $60 \cdot 10^{12}$ years (10^{-13} rad/yr),[17] and debate persists over whether there is *any* rotation. However, if rotation were found, interpretation of observations in a frame tied to the universe would have to be corrected for the fictitious forces inherent in such rotation in classical physics and special relativity, or interpreted as the curvature of spacetime and the motion of matter along the geodesics in general relativity.

When quantum effects are important, there are additional conceptual complications that arise in quantum reference frames.

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Background[edit]

A brief comparison of inertial frames in special relativity and in Newtonian mechanics, and the role of absolute space is next.

A set of frames where the laws of physics are simple[edit]

According to the first postulate of special relativity, all physical laws take their simplest form in an inertial frame, and there exist multiple inertial frames interrelated by uniform translation: [18]

Special principle of relativity: If a system of coordinates K is chosen so that, in relation to it, physical laws hold good in their simplest form, the same laws hold good in relation to any other system of coordinates K' moving in uniform translation relatively to K.

— *Albert Einstein: The foundation of the general theory of relativity, Section A, §1*

This simplicity manifests in that inertial frames have self-contained physics without the need for external causes, while physics in non-inertial frames have external causes.[3] The principle of simplicity can be used within Newtonian physics as well as in special relativity; see Nagel[19] and also Blagojević.[20]

The laws of Newtonian mechanics do not always hold in their simplest form...If, for instance, an observer is placed on a disc rotating relative to the earth, he/she will sense a 'force' pushing him/her toward the periphery of the disc, which is not caused by any interaction with other bodies. Here, the acceleration is not the consequence of the usual force, but of the so-called inertial force. Newton's laws hold in their simplest form only in a family of reference frames, called inertial frames. This fact represents the essence of the Galilean principle of relativity: The laws of mechanics have the same form in all inertial frames.

— *Milutin Blagojević: Gravitation and Gauge Symmetries, p. 4*

In practical terms, the equivalence of inertial reference frames means that scientists within a box moving uniformly cannot determine their absolute velocity by any experiment (otherwise the differences would set up an absolute standard reference frame).[21][22] According to this definition, supplemented with the constancy of the

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speed of light, inertial frames of reference transform among themselves according to the Poincaré group of symmetry transformations, of which the Lorentz transformations are a subgroup.[23] In Newtonian mechanics, which can be viewed as a limiting case of special relativity in which the speed of light is infinite, inertial frames of reference are related by the Galilean groupof symmetries.

Absolute space[edit]

Main article: Absolute space and time

Newton posited an absolute space considered well approximated by a frame of reference stationary relative to the fixed stars. An inertial frame was then one in uniform translation relative to absolute space. However, some scientists (called "relativists" by Mach[24]), even at the time of Newton, felt that absolute space was a defect of the formulation, and should be replaced.

Indeed, the expression *inertial frame of reference* (German: *Inertialsystem*) was coined by Ludwig Lange in 1885, to replace Newton's definitions of "absolute space and time" by a more operational definition.[25][26] As translated by Iro, Lange proposed the following definition:[27]

A reference frame in which a mass point thrown from the same point in three different (non co-planar) directions follows rectilinear paths each time it is thrown, is called an inertial frame.

A discussion of Lange's proposal can be found in Mach.[24]

The inadequacy of the notion of "absolute space" in Newtonian mechanics is spelled out by Blagojević:[28]

- The existence of absolute space contradicts the internal logic of classical mechanics since, according to Galilean principle of relativity, none of the the inertial frames can be singled out.
- Absolute space does not explain inertial forces since they are related to acceleration with respect to any one of the inertial frames.

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- Absolute space acts on physical objects by inducing their resistance to acceleration but it cannot be acted upon.

— *Milutin Blagojević: Gravitation and Gauge Symmetries, p. 5*

The utility of operational definitions was carried much further in the special theory of relativity.[29] Some historical background including Lange's definition is provided by DiSalle, who says in summary:[30]

The original question, "relative to what frame of reference do the laws of motion hold?" is revealed to be wrongly posed. For the laws of motion essentially determine a class of reference frames, and (in principle) a procedure for constructing them.

— *Robert DiSalle Space and Time: Inertial Frames*

Newton's inertial frame of reference[edit]

Figure 1: Two frames of reference moving with relative velocity . Frame *S'* has an arbitrary but fixed rotation with respect to frame *S*. They are both *inertial frames*provided a body not subject to forces appears to move in a straight line. If that motion is seen in one frame, it will also appear that way in the other.

Within the realm of Newtonian mechanics, an inertial frame of reference, or inertial reference frame, is one in which Newton's first law of motion is valid.[31] However, the principle of special relativity generalizes the notion of inertial frame to include all physical laws, not simply Newton's first law.

Newton viewed the first law as valid in any reference frame that is in uniform motion relative to the fixed stars;[32] that is, neither rotating nor accelerating relative to the stars.[33] Today the notion of "absolute space" is abandoned, and an inertial frame in the field of classical mechanics is defined as:[34][35]

An inertial frame of reference is one in which the motion of a particle not subject to forces is in a straight line at constant speed.

Hence, with respect to an inertial frame, an object or body accelerates only when a physical force is applied, and (following Newton's first law of motion), in the absence of a net force, a body at rest will remain at rest and a body in motion will continue to move uniformly—that is, in a straight line and at constant speed. Newtonian inertial frames transform among each other according to the Galilean group of symmetries.

If this rule is interpreted as saying that straight-line motion is an indication of zero net force, the rule does not identify inertial reference frames because straight-line motion can be observed in a variety of frames. If the rule is interpreted as defining an inertial frame, then we have to be able to determine when zero net force is applied. The problem was summarized by Einstein:[36]

The weakness of the principle of inertia lies in this, that it involves an argument in a circle: a mass moves without acceleration if it is sufficiently far from other bodies; we know that it is sufficiently far from other bodies only by the fact that it moves without acceleration.

— *Albert Einstein: The Meaning of Relativity, p. 58*

There are several approaches to this issue. One approach is to argue that all real forces drop off with distance from their sources in a known manner, so we have only to be sure that a body is far enough away from all sources to ensure that no force is present.[37] A possible issue with this approach is the historically long-lived view that the distant universe might affect matters (Mach's principle). Another approach is to identify all real sources for real forces and account for them. A possible issue with this approach is that we might miss something, or account inappropriately for their influence, perhaps, again, due to Mach's principle and an incomplete understanding of the universe. A third approach is to look at the way the forces transform when we shift reference frames. Fictitious forces, those that arise due to the acceleration of a frame, disappear in inertial frames, and have complicated rules of transformation in general cases. On the basis of universality of physical law and the request for frames where the laws are most simply expressed, inertial frames are distinguished by the absence of such fictitious forces.

Newton enunciated a principle of relativity himself in one of his corollaries to the laws of motion:[38][39]

The motions of bodies included in a given space are the same among themselves, whether that space is at rest or moves uniformly forward in a straight line.

— *Isaac Newton: Principia, Corollary V, p. 88 in Andrew Motte translation*

This principle differs from the special principle in two ways: first, it is restricted to mechanics, and second, it makes no mention of simplicity. It shares with the special principle the invariance of the form of the description among mutually translating reference frames.[40] The role of fictitious forces in classifying reference frames is pursued further below.

Separating non-inertial from inertial reference frames[edit]

Theory[edit]

Main article: Fictitious force

See also: Non-inertial frame, Rotating spheres, and Bucket argument

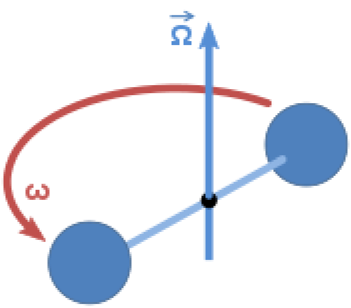

Figure 2: Two spheres tied with a string and rotating at an angular rate ω. Because of the rotation, the string tying the spheres together is under tension.

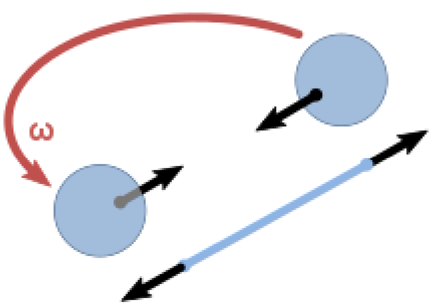

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Figure 3: Exploded view of rotating spheres in an inertial frame of reference showing the centripetal forces on the spheres provided by the tension in the tying string.

Inertial and non-inertial reference frames can be distinguished by the absence or presence of fictitious forces, as explained shortly.[7][8]

The effect of this being in the noninertial frame is to require the observer to introduce a fictitious force into his calculations….

— *Sidney Borowitz and Lawrence A Bornstein in A Contemporary View of Elementary Physics, p. 138*

The presence of fictitious forces indicates the physical laws are not the simplest laws available so, in terms of the special principle of relativity, a frame where fictitious forces are present is not an inertial frame:[41]

The equations of motion in a non-inertial system differ from the equations in an inertial system by additional terms called inertial forces. This allows us to detect experimentally the non-inertial nature of a system.

— *V. I. Arnol'd: Mathematical Methods of Classical Mechanics Second Edition, p. 129*

Bodies in non-inertial reference frames are subject to so-called *fictitious* forces (pseudo-forces); that is, forces that result from the acceleration of the reference frame itself and not from any physical force acting on the body. Examples of fictitious forces are the centrifugal force and the Coriolis force in rotating reference frames.

How then, are "fictitious" forces to be separated from "real" forces? It is hard to apply the Newtonian definition of an inertial frame without this separation. For example, consider a stationary object in an inertial frame. Being at rest, no net force is applied. But in a frame rotating about a fixed axis, the object appears to move in a circle, and is subject to centripetal force (which is made up of the Coriolis force and the centrifugal force). How can we decide that the rotating frame is a non-inertial frame? There are two approaches to this resolution: one approach is to look for the origin of the fictitious forces (the Coriolis force and the centrifugal force). We will find there are no sources for these forces, no associated force carriers, no originating bodies.[42] A second approach is to look at a variety of frames of reference. For any inertial frame, the Coriolis force and the centrifugal force disappear, so application of the principle of special relativity would identify these frames where the forces disappear as sharing the same and the simplest physical laws, and hence rule that the rotating frame is not an inertial frame.

Newton examined this problem himself using rotating spheres, as shown in Figure 2 and Figure 3. He pointed out that if the spheres are not rotating, the tension in the tying string is measured as zero in every frame of reference.[43] If the spheres only appear to rotate (that is, we are watching stationary spheres from a rotating frame), the zero tension in the string is accounted for by observing that the centripetal force is supplied by the centrifugal and Coriolis forces in combination, so no tension is needed. If the spheres really are rotating, the tension observed is exactly the centripetal force required by the circular motion. Thus, measurement of the tension in the string identifies the inertial frame: it is the one where the tension in the string provides exactly the centripetal force demanded by the motion as it is observed in that frame, and not a different value. That is, the inertial frame is the one where the fictitious forces vanish.So much for fictitious forces due to rotation. However, for linear acceleration, Newton expressed the idea of undetectability of straight-line accelerations held in common:[39]

If bodies, any how moved among themselves, are urged in the direction of parallel lines by equal accelerative forces, they will continue to move among themselves, after the same manner as if they had been urged by no such forces.

— *Isaac Newton: Principia Corollary VI, p. 89, in Andrew Motte translation*

This principle generalizes the notion of an inertial frame. For example, an observer confined in a free-falling lift will assert that he himself is a valid inertial frame, even if he is accelerating under gravity, so long as he has no knowledge about anything outside the lift. So, strictly speaking, inertial frame is a relative concept. With this in mind, we can define inertial frames collectively as a set of frames which are stationary or moving at constant velocity with respect to each other, so that a single inertial frame is defined as an element of this set.

For these ideas to apply, everything observed in the frame has to be subject to a base-line, common acceleration shared by the frame itself. That situation would apply, for example, to the elevator example, where all objects are subject to the same gravitational acceleration, and the elevator itself accelerates at the same rate.

In 1899 the astronomer Karl Schwarzschild pointed out an observation about double stars. The motion of two stars orbiting each other is planar, the two orbits of the stars of the system lie in a plane. In the case of sufficiently near double star systems, it can be seen from Earth whether the perihelion of the orbits of the two stars remains pointing in the same direction with respect to the solar system. Schwarzschild pointed out that that was invariably seen: the direction of the angular momentum of all observed double star systems remains fixed with respect to the direction of the angular momentum of the Solar system. The logical inference is that just like gyroscopes, the angular momentum of all celestial bodies is angular momentum with respect to a universal inertial space.[44]

Applications[edit]

Inertial navigation systems used a cluster of gyroscopes and accelerometers to determine accelerations relative to inertial space. After a gyroscope is spun up in a particular orientation in inertial space, the law of conservation of angular momentum requires that it retain that orientation as long as no external forces are applied to it.[45]:59 Three orthogonal gyroscopes establish an inertial reference frame, and the accelerators measure acceleration relative to that frame. The accelerations, along with a clock, can then be used to calculate the change in position. Thus, inertial navigation is a form of dead reckoning that requires no external input, and therefore cannot be jammed by any external or internal signal source.[46]

A gyrocompass, employed for navigation of seagoing vessels, finds the geometric north. It does so, not by sensing the Earth's magnetic field, but by using inertial space as its reference. The outer casing of the gyrocompass device is held in such a way that it remains aligned with the local plumb line. When the gyroscope wheel inside the gyrocompass device is spun up, the way the gyroscope wheel is suspended causes the gyroscope wheel to gradually align its spinning axis with the Earth's axis. Alignment with the Earth's axis is the only direction for which the gyroscope's spinning axis can be stationary with respect to the Earth and not be required to change direction with respect to inertial space. After being spun up, a gyrocompass can reach the direction of alignment with the Earth's axis in as little as a quarter of an hour.[47]

Newtonian mechanics[edit]

Main article: Newton's laws of motion

Classical mechanics, which includes relativity, assumes the equivalence of all inertial reference frames. Newtonian mechanics makes the additional assumptions of absolute spaceand absolute time. Given these two assumptions, the coordinates of the same event (a point in space and time) described in two inertial reference frames are related by a Galilean transformation.

where $\mathbf{r}_0$ and t_0 represent shifts in the origin of space and time, and $\mathbf{v}$ is the relative velocity of the two inertial reference frames. Under Galilean transformations, the time $t_2 - t_1$between two events is the same for all inertial reference frames and the distance between two simultaneous events (or, equivalently, the length of any object, $|\mathbf{r}_2 - \mathbf{r}_1|$) is also the same.

Special relativity[edit]

Main articles: Special relativity and Introduction to special relativity

Einstein's theory of special relativity, like Newtonian mechanics, assumes the equivalence of all inertial reference frames, but makes an additional assumption, foreign to Newtonian mechanics, namely, that in free space light always is propagated with the speed of light c_0, a defined value independent of its direction of propagation and its frequency, and also independent of the state of motion of the

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emitting body. This second assumption has been verified experimentally[48] and leads to counter-intuitive deductions including:

- time dilation (moving clocks tick more slowly)
- length contraction (moving objects are shortened in the direction of motion)
- relativity of simultaneity (simultaneous events in one reference frame are not simultaneous in almost all frames moving relative to the first).

These deductions are logical consequences of the stated assumptions, and are general properties of space-time, typically without regard to a consideration of properties pertaining to the structure of individual objects like atoms or stars, nor to the mechanisms of clocks.

These effects are expressed mathematically by the Lorentz transformation

where shifts in origin have been ignored, the relative velocity is assumed to be in

the -direction and the Lorentz factor γ is defined by:

The Lorentz transformation is equivalent to the Galilean transformation in the limit $c_0 \rightarrow \infty$ (a hypothetical case) or $v \rightarrow 0$ (low speeds).

Under Lorentz transformations, the time and distance between events may differ among inertial reference frames; however, the Lorentz scalar distance *s* between two events is the same in all inertial reference frames

From this perspective, the speed of light is only accidentally a property of light, and is rather a property of spacetime, a conversion factor between conventional time units (such as seconds) and length units (such as meters).

Incidentally, because of the limitations on speeds faster than the speed of light, notice that in a rotating frame of reference (which is a non-inertial frame, of course) stationarity is not possible at arbitrary distances because at large radius the object would move faster than the speed of light.[49]

General relativity[edit]

Main articles: General relativity and Introduction to general relativity

See also: Equivalence principle and Eötvös experiment

General relativity is based upon the principle of equivalence:[50][51]

There is no experiment observers can perform to distinguish whether an acceleration arises because of a gravitational force or because their reference frame is accelerating.

— *Douglas C. Giancoli, Physics for Scientists and Engineers with Modern Physics, p. 155.*

This idea was introduced in Einstein's 1907 article "Principle of Relativity and Gravitation" and later developed in 1911.[52] Support for this principle is found in the Eötvös experiment, which determines whether the ratio of inertial to gravitational mass is the same for all bodies, regardless of size or composition. To date no difference has been found to a few parts in 10^{11}.[53] For some discussion of the subtleties of the Eötvös experiment, such as the local mass distribution around the experimental site (including a quip about the mass of Eötvös himself), see Franklin.[54]

Einstein's general theory modifies the distinction between nominally "inertial" and "noninertial" effects by replacing special relativity's "flat" Minkowski Space with a metric that produces non-zero curvature. In general relativity, the principle of inertia is replaced with the principle of geodesic motion, whereby objects move in a way dictated by the curvature of spacetime. As a consequence of this curvature, it is not a given in general relativity that inertial objects moving at a particular rate with respect to each other will continue to do so. This phenomenon of geodesic deviation means that inertial frames of reference do not exist globally as they do in Newtonian mechanics and special relativity.

However, the general theory reduces to the special theory over sufficiently small regions of spacetime, where curvature effects become less important and the earlier inertial frame arguments can come back into play.[55][56] Consequently, modern special relativity is now sometimes described as only a "local theory".[57]

From Wikipedia, the free encyclopedia

This article is about a type of acceleration. For other uses, see G-Force (disambiguation).

This article is about effects of long acceleration. For transient acceleration, see mechanical shock.

In straight and level flight, lift (L) equals weight (W). In a banked turn of 60°, lift equals double the weight (L=2W). The pilot experiences 2 g and a doubled weight. The steeper the bank, the greater the g-forces.

This top-fuel dragster can accelerate from zero to 160 kilometres per hour (99 mph) in 0.86 seconds. This is a horizontal acceleration of 5.3 g. Combined with the vertical g-force in the stationary case the Pythagorean theorem yields a g force of 5.4 g.

The g-force (with g from gravitational) is a measurement of the type of acceleration that causes a perception of weight. Despite the name, it is incorrect to consider g-force a fundamental force, as "g-force" (lower case character) is a type of acceleration that can be measured with an accelerometer. Since g-force accelerations indirectly produce weight, any g-force can be described as a "weight per unit mass" (see the synonym specific weight). When the g-force acceleration is produced by the surface of one object being pushed by the surface of another object, the reaction-force to this push produces an equal and opposite weight for every unit of an object's mass. The types of forces involved are transmitted through objects by interior mechanical stresses. The g-force acceleration (save for certain electromagnetic force influences) is the cause of an object's acceleration in relation to free-fall.[1][2]

The g-force acceleration experienced by an object is due to the vector sum of all non-gravitational and non-electromagnetic forces acting on an object's freedom to move. In practice, as noted, these are surface-contact forces between objects. Such forces cause stresses and strains on objects, since they must be transmitted from an object surface. Because of these strains, large g-forces may be destructive.

Gravitation acting alone does not produce a g-force, even though g-forces are expressed in multiples of the acceleration of a standard gravity. Thus, the standard gravitational acceleration at the Earth's surface produces g-force only indirectly, as a result of resistance to it by mechanical forces. These mechanical forces actually produce the g-force acceleration on a mass. For example, the 1 g force on an object sitting on the Earth's surface is caused by mechanical force exerted in the upward direction by the ground, keeping the object from going into free-fall. The upward contact-force from the ground ensures that an object at rest on the Earth's surface is accelerating relative to the free-fall condition. (Free fall is the path that the object would follow when falling freely toward the Earth's center). Stress inside the object is ensured from the fact that the ground contact forces are transmitted only from the point of contact with the ground.

Objects allowed to free-fall in an inertial trajectory under the influence of gravitation only, feel no g-force acceleration, a condition known as zero-g (which means zero g-force). This is demonstrated by the "zero-g" conditions inside a freely falling elevator falling toward the Earth's center (in vacuum), or (to good approximation) conditions inside a spacecraft in Earth orbit. These are examples of coordinate acceleration (a change in velocity) without a sensation of weight. The experience of no g-force (zero-g), however it is produced, is synonymous with weightlessness.

In the absence of gravitational fields, or in directions at right angles to them, proper and coordinate accelerations are the same, and any coordinate acceleration must be produced by a corresponding g-force acceleration. An example here is a rocket in free space, in which simple changes in velocity are produced by the engines, and produce g-forces on the rocket and passenger

Unit and measurement[edit]

The unit of measure of acceleration in the International System of Units (SI) is m/s^2. However, to distinguish acceleration relative to free-fall from simple acceleration (rate of change of velocity), the unit **g** (or ***g***) is often used. One *g* is the acceleration due to gravity at the Earth's surface and is the standard gravity (symbol: g_n), defined as 9.80665 metres per second squared,[3] or

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equivalently 9.80665 newtons of force per kilogram of mass. Note that the *unit definition* does not vary with location—the g-force when standing on the moon is about 0.181 g.

The unit **g** is not one of the SI units, which uses "g" for gram. Also, "g" should not be confused with "G", which is the standard symbol for the gravitational constant.[4] This notation is commonly used in aviation, especially in aerobatic or combat military aviation, to describe the increased forces that must be overcome by pilots in order to remain conscious and not G-LOC (G-induced loss of consciousness).[5]

Measurement of g-force is typically achieved using an accelerometer (see discussion below in Measuring g-force using an accelerometer). In certain cases, g-forces may be measured using suitably calibrated scales. Specific force is another name that has been used for g-force.

Acceleration and forces[edit]

The term g-**force** is technically incorrect as it is a measure of *acceleration*, not force. While acceleration is a vector quantity, g-force accelerations ("g-forces" for short) are often expressed as a scalar, with positive g-forces pointing downward (indicating upward acceleration), and negative g-forces pointing upward. Thus, a g-force is a vector acceleration. It is an acceleration that must be produced by a mechanical force, and cannot be produced by simple gravitation. Objects acted upon *only* by gravitation, experience (or "feel") no g-force, and are weightless.

G-forces, when multiplied by a mass upon which they act, are associated with a certain type of mechanical *force* in the correct sense of the term **force**, and this force produces compressive stress and tensile stress. Such forces result in the operational sensation of weight, but the equation carries a sign change due to the definition of positive weight in the direction downward, so the direction of weight-force is opposite to the direction of g-force acceleration:

Weight = mass × −g-force

The reason for the minus sign is that the actual *force* (i.e., measured weight) on an object produced by a g-force is in the opposite direction to the sign of the g-force,

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since in physics, weight is not the force that produces the acceleration, but rather the equal-and-opposite reaction force to it. If the direction upward is taken as positive (the normal Cartesian convention) then *positive* g-force (an acceleration vector that points upward) produces a force/weight on any mass, that acts *downward* (an example is positive-g acceleration of a rocket launch, producing downward weight). In the same way, a *negative-g force* is an acceleration vector *downward* (the negative direction on the y axis), and this acceleration downward produces a weight-force in a direction *upward* (thus pulling a pilot upward out of the seat, and forcing blood toward the head of a normally oriented pilot).

If a g-force (acceleration) is vertically upward and is applied by the ground (which is accelerating through space-time) or applied by the floor of an elevator to a standing person, most of the body experiences compressive stress which at any height, if multiplied by the area, is the related mechanical force, which is the product of the g-force and the supported mass (the mass above the level of support, including arms hanging down from above that level). At the same time, the arms themselves experience a tensile stress, which at any height, if multiplied by the area, is again the related mechanical force, which is the product of the g-force and the mass hanging below the point of mechanical support. The mechanical resistive force spreads from points of contact with the floor or supporting structure, and gradually decreases toward zero at the unsupported ends (the top in the case of support from below, such as a seat or the floor, the bottom for a hanging part of the body or object). With compressive force counted as negative tensile force, the rate of change of the tensile force in the direction of the g-force, per unit mass (the change between parts of the object such that the slice of the object between them has unit mass), is equal to the g-force plus the non-gravitational external forces on the slice, if any (counted positive in the direction opposite to the g-force).

For a given g-force the stresses are the same, regardless of whether this g-force is caused by mechanical resistance to gravity, or by a coordinate-acceleration (change in velocity) caused by a mechanical force, or by a combination of these. Hence, for people all mechanical forces feels exactly the same whether they cause coordinate acceleration or not. For objects likewise, the question of whether they can withstand the mechanical g-force without damage is the same for any type of g-force. For example, upward acceleration (e.g., increase of speed when going up or decrease of speed when going down) on Earth feels the same as being stationary on a celestial body with a higher surface gravity. Gravitation acting alone does not produce any g-force; g-force is only produced from mechanical pushes and pulls. For a free body (one that is free to move in space) such g-forces only arise as the "inertial" path that is the natural effect of gravitation, or the natural effect of the inertia of mass, is modified. Such modification may only arise from influences other than gravitation.

Examples of important situations involving g-forces include:

- The g-force acting on a stationary object resting on the Earth's surface is 1 g (upwards) and results from the resisting reaction of the Earth's surface bearing upwards equal to an acceleration of 1 g, and is equal and opposite to gravity. The number 1 is approximate, depending on location.
- The g-force acting on an object in any weightless environment such as free-fall in a vacuum is 0 g.
- The g-force acting on an object under acceleration can be much greater than 1 g, for example, the dragster pictured at top right can exert a horizontal g-force of 5.3 when accelerating.
- The g-force acting on an object under acceleration may be downwards, for example when cresting a sharp hill on a roller coaster.
- If there are no other external forces than gravity, the g-force in a rocket is the thrust per unit mass. Its magnitude is equal to the thrust-to-weight ratio times g, and to the consumption of delta-v per unit time.
- In the case of a shock, e.g., a collision, the g-force can be very large during a short time.

A classic example of negative g-force is in a fully inverted roller coaster which is accelerating (changing velocity) toward the ground. In this case, the roller coaster riders are accelerated toward the ground faster than gravity would accelerate them, and are thus pinned upside down in their seats. In this case, the mechanical force exerted by the seat causes the g-force by altering the path of the passenger downward in a way that differs from gravitational acceleration. The difference in downward motion, now faster than gravity would provide, is caused by the push of the seat, and it results in a g-force toward the ground.

All "coordinate accelerations" (or lack of them), are described by Newton's laws of motion as follows:

The *Second Law of Motion*, the law of acceleration states that: $F = ma$., meaning that a force F acting on a body is equal to the mass m of the body times its acceleration a.

The *Third Law of Motion*, the law of reciprocal actions states that: all forces occur in pairs, and these two forces are equal in magnitude and opposite in direction. Newton's third law of motion means that not only does gravity behave as a force acting downwards on, say, a rock held in your hand but also that the rock exerts a force on the Earth, equal in magnitude and opposite in direction.

This acrobatic airplane is pulling up in a +g maneuver; the pilot is experiencing several g's of inertial acceleration in addition to the force of gravity. The cumulative vertical axis forces acting upon his body make him momentarily 'weigh' many times more than normal.

In an airplane, the pilot's seat can be thought of as the hand holding the rock, the pilot as the rock. When flying straight and level at 1 g, the pilot is acted upon by the force of gravity. His weight (a downward force) is 725 newtons (163 lb_f). In accordance with Newton's third law, the plane and the seat underneath the pilot provides an equal and opposite force pushing upwards with a force of 725 N (163 lb_f). This mechanical force provides the 1.0 g-force upward proper acceleration on the pilot, even though this velocity in the upward direction does not change (this is similar to the situation of a person standing on the ground, where the ground provides this force and this g-force).

If the pilot were suddenly to pull back on the stick and make his plane accelerate upwards at 9.8 m/s^2, the total g-force on his body is 2 g, half of which comes from the seat pushing the pilot to resist gravity, and half from the seat pushing the pilot to cause his upward acceleration—a change in velocity which also is a *proper acceleration* because it also differs from a free fall trajectory. Considered in the frame of reference of the plane his body is now generating a force of 1,450 N (330 lb_f) downwards into his seat and the seat is simultaneously pushing upwards with an equal force of 1,450 N (330 lb_f).

Unopposed acceleration due to mechanical forces, and consequentially g-force, is experienced whenever anyone rides in a vehicle because it always causes a proper acceleration, and (in the absence of gravity) also always a coordinate acceleration (where velocity changes). Whenever the vehicle changes either direction or speed, the occupants feel lateral (side to side) or longitudinal (forward and backwards) forces produced by the mechanical push of their seats.

The expression "1 g = 9.80665 m/s^2" means that *for every second that elapses*, velocity changes 9.80665 meters per second (≡35.30394 km/h). This rate of change in velocity can also be denoted as 9.80665 (meter per second) per second, or 9.80665 m/s^2. For example: An acceleration of 1 g equates to a rate of change in velocity of approximately 35 kilometres per hour (22 mph) for each second that elapses. Therefore, if an automobile is capable of braking at 1 g and is traveling at 35 kilometres per hour (22 mph) it can brake to a standstill in one second and the driver will experience a deceleration of 1 g. The automobile traveling at three times this speed, 105 km/h (65 mph), can brake to a standstill in three seconds.

In the case of an increase in speed from 0 to v with constant acceleration within a distance of s this acceleration is $v^2/(2s)$.

Preparing an object for g-tolerance (not getting damaged when subjected to a high g-force) is called g-hardening.[*citation needed*] This may apply to, e.g., instruments in a projectile shot by a gun.

Human tolerance[edit]

See also: Jerk (physics) § Physiological effects and human perception

Semilog graph of the limits of tolerance of humans to linear acceleration[6]

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Human tolerances depend on the magnitude of the g-force, the length of time it is applied, the direction it acts, the location of application, and the posture of the body.[7][8]:350

The human body is flexible and deformable, particularly the softer tissues. A hard slap on the face may briefly impose hundreds of g locally but not produce any real damage; a constant 16 g for a minute, however, may be deadly. When vibration is experienced, relatively low peak g levels can be severely damaging if they are at the resonance frequency of organs or connective tissues.

To some degree, g-tolerance can be trainable, and there is also considerable variation in innate ability between individuals. In addition, some illnesses, particularly cardiovascular problems, reduce g-tolerance.

Vertical[edit]

Aircraft pilots (in particular) sustain g-forces along the axis aligned with the spine. This causes significant variation in blood pressure along the length of the subject's body, which limits the maximum g-forces that can be tolerated.

Positive, or "upward" g, drives blood downward to the feet of a seated or standing person (more naturally, the feet and body may be seen as being driven by the upward force of the floor and seat, upward around the blood). Resistance to positive g varies. A typical person can handle about 5 g_0 (49 m/s^2) (meaning some people might pass out when riding a higher-g roller coaster, which in some cases exceeds this point) before losing consciousness, but through the combination of special g-suits and efforts to strain muscles—both of which act to force blood back into the brain—modern pilots can typically handle a sustained 9 g_0 (88 m/s^2) (see High-G training)[*citation needed*].

In aircraft particularly, vertical g-forces are often positive (force blood towards the feet and away from the head); this causes problems with the eyes and brain in particular. As positive vertical g-force is progressively increased (such as in a centrifuge) the following symptoms may be experienced:

- **Grey-out,** where the vision loses hue, easily reversible on levelling out.

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- **Tunnel vision**, where peripheral vision is progressively lost.
- **Blackout**, a loss of vision while consciousness is maintained, caused by a lack of blood to the head.
- **G-LOC**, a g-force induced **l**oss **o**f **c**onsciousness.[9]
- **Death**, if g-forces are not quickly reduced, death can occur.[10]

Resistance to "negative" or "downward" g, which drives blood to the head, is much lower. This limit is typically in the −2 to −3 g_0 (−20 to −29 m/s^2) range. This condition is sometimes referred to as red out where vision is figuratively reddened[11] due to the blood laden lower eyelid being pulled into the field of vision[12] Negative g is generally unpleasant and can cause damage. Blood vessels in the eyes or brain may swell or burst under the increased blood pressure, resulting in degraded sight or even blindness.

Horizontal[edit]

The human body is better at surviving g-forces that are perpendicular to the spine. In general when the acceleration is forwards (subject essentially lying on their back, colloquially known as "eyeballs in"[13]) a much higher tolerance is shown than when the acceleration is backwards (lying on their front, "eyeballs out") since blood vessels in the retina appear more sensitive in the latter direction[*citation needed*].

Early experiments showed that untrained humans were able to tolerate a range of accelerations depending on the time of exposure. This ranged from as much as 20 g for less than 10 seconds, to 10 g for 1 minute, and 6 g for 10 minutes for both eyeballs in and out.[14] These forces were endured with cognitive facilities intact, as subjects were able to perform simple physical and communication tasks. The tests were determined to not cause long or short term harm although tolerance was quite subjective, with only the most motivated non-pilots capable of completing tests.[15] The record for peak experimental horizontal g-force tolerance is held by acceleration pioneer John Stapp, in a series of rocket sled deceleration experiments culminating in a late 1954 test in which he was clocked in a little over a second from a land speed of Mach 0.9. He survived a peak "eyeballs-out" acceleration of 46.2 times the acceleration of gravity, and more than 25 g for 1.1 seconds, proving that the human body is capable of this. Stapp lived another 45 years to age 89[16]without any ill effects.[17]

The highest recorded G-force experienced by someone who lived to tell the tale occurred in an Indycar motor race when a car driven by Kenny Bräck impacted a catch fence and recorded a peak force of 214 g. Although he experienced multiple fractures he made a full recovery.[18][19]

Short duration shock, impact, and jerk[edit]

Impact and mechanical shock are usually used to describe a high kinetic energy, short term excitation. A shock pulse is often measured by its peak acceleration in g-s and the pulse duration. Vibration is a periodic oscillation which can also be measured in g-s as well as frequency. The dynamics of these phenomena are what distinguish them from the g-forces caused by a relatively longer term accelerations.

After a free fall from a height the shock on an object during impact is g,

where is the distance covered during the impact. For example, a stiff and compact object dropped from 1 m that impacts over a distance of 1 mm is subjected to a 1000 g deceleration.

Jerk is the rate of change of acceleration. In SI units, jerk is expressed as m/s^3; it can also be expressed in standard gravity per second (*g*/s; 1 *g*/s ≈ 9.81 m/s^3).

Other biological responses[edit]

Recent research carried out on extremophiles in Japan involved a variety of bacteria including *E. coli* and *Paracoccus denitrificans* being subject to conditions of extreme gravity. The bacteria were cultivated while being rotated in an ultracentrifuge at high speeds corresponding to 403,627 g. *Paracoccus denitrificans* was one of the bacteria which displayed not only survival but also robust cellular growth under these conditions of hyperacceleration which are usually only to be found in cosmic environments, such as on very massive stars or in the shock waves of supernovas. Analysis showed that the small size of prokaryotic cells is essential for successful growth under hypergravity. The research has implications on the feasibility of panspermia.[20][21]

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Typical examples[edit]

Main article: Orders of magnitude (acceleration)

* Including contribution from resistance to gravity.
† Directed 40 degrees from horizontal.

Measurement using an accelerometer[edit]

The Superman: Escape from Krypton roller coaster at Six Flags Magic Mountainprovides 6.5 seconds of ballistic weightlessness.

An accelerometer, in its simplest form, is a damped mass on the end of a spring, with some way of measuring how far the mass has moved on the spring in a particular direction, called an 'axis'.

Accelerometers are often calibrated to measure g-force along one or more axes. If a stationary, single-axis accelerometer is oriented so that its measuring axis is horizontal, its output will be 0 g, and it will continue to be 0 g if mounted in an automobile traveling at a constant velocity on a level road. When the driver presses on the brake or gas pedal, the accelerometer will register positive or negative acceleration.

If the accelerometer is rotated by 90° so that it is vertical, it will read +1 g upwards even though stationary. In that situation, the accelerometer is subject to two forces: the gravitational force and the ground reaction force of the surface it is resting on. Only the latter force can be measured by the accelerometer, due to mechanical interaction between the accelerometer and the ground. The reading is the acceleration the instrument would have if it were exclusively subject to that force.

A three-axis accelerometer will output zero-g on all three axes if it is dropped or otherwise put into a ballistic trajectory (also known as an inertialtrajectory), so that it experiences "free fall," as do astronauts in orbit (astronauts experience small tidal accelerations called microgravity, which are neglected for the sake of discussion here). Some amusement park rides can provide several seconds at near-zero g. Riding NASA's "Vomit Comet" provides near-zero g for about 25 seconds at a time.

Accelerometer

From Wikipedia, the free encyclopedia

An accelerometer is a device that measures proper acceleration.[1] Proper acceleration, being the acceleration (or rate of change of velocity) of a body in its own instantaneous rest frame,[2] is not the same as coordinate acceleration, being the acceleration in a fixed coordinate system. For example, an accelerometer at rest on the surface of the Earth will measure an acceleration due to Earth's gravity, straight upwards (by definition) of g ≈ 9.81 m/s2. By contrast, accelerometers in free fall (falling toward the center of the Earth at a rate of about 9.81 m/s2) will measure zero.

Accelerometers have multiple applications in industry and science. Highly sensitive accelerometers are components of inertial navigation systems for aircraft and missiles. Accelerometers are used to detect and monitor vibration in rotating machinery. Accelerometers are used in tablet computers and digital cameras so that images on screens are always displayed upright. Accelerometers are used in drones for flight stabilisation. Coordinated accelerometers can be used to measure differences in proper acceleration, particularly gravity, over their separation in space; i.e., gradient of the gravitational field. This gravity gradiometry is useful because absolute gravity is a weak effect and depends on local density of the Earth which is quite variable.

Single- and multi-axis models of accelerometer are available to detect magnitude and direction of the proper acceleration, as a vector quantity, and can be used to sense orientation (because direction of weight changes), coordinate acceleration, vibration, shock, and falling in a resistive medium (a case where the proper acceleration changes, since it starts at zero, then increases). Micromachined microelectromechanical systems (MEMS) accelerometers are increasingly present in portable electronic devices and video game controllers, to detect the position of the device or provide for game input

Physical principles[edit]

An accelerometer measures proper acceleration, which is the acceleration it experiences relative to freefall and is the acceleration felt by people and objects.[2] Put another way, at any point in spacetime the equivalence principle guarantees the existence of a local inertial frame, and an accelerometer measures the acceleration relative to that frame.[3] Such accelerations are popularly denoted g-force; i.e., in comparison to standard gravity.

An accelerometer at rest relative to the Earth's surface will indicate approximately 1 g *upwards*, because any point on the Earth's surface is accelerating upwards relative to the local inertial frame (the frame of a freely falling object near the surface). To obtain the acceleration due to motion with respect to the Earth, this "gravity offset" must be subtracted and corrections made for effects caused by the Earth's rotation relative to the inertial frame.

The reason for the appearance of a gravitational offset is Einstein's equivalence principle,[4] which states that the effects of gravity on an object are indistinguishable from acceleration. When held fixed in a gravitational field by, for example, applying a ground reaction force or an equivalent upward thrust, the reference frame for an accelerometer (its own casing) accelerates upwards with respect to a free-falling reference frame. The effects of this acceleration are indistinguishable from any other acceleration experienced by the instrument, so that an accelerometer cannot detect the difference between sitting in a rocket on the launch pad, and being in the same rocket in deep space while it uses its engines to accelerate at 1 g. For similar reasons, an accelerometer will read *zero* during any type of free fall. This includes use in a coasting spaceship in deep space far from any mass, a spaceship orbiting the Earth, an airplane in a parabolic "zero-g" arc, or any free-fall in vacuum. Another example is free-fall at a sufficiently high altitude that atmospheric effects can be neglected.

However this does not include a (non-free) fall in which air resistance produces drag forces that reduce the acceleration, until constant terminal velocity is reached. At terminal velocity the accelerometer will indicate 1 g acceleration upwards. For the same reason a skydiver, upon reaching terminal velocity, does not feel as though he or she were in "free-fall", but rather experiences a feeling similar to being supported (at 1 g) on a "bed" of uprushing air.

Acceleration is quantified in the SI unit metres per second per second (m/s^2), in the cgs unit gal (Gal), or popularly in terms of standard gravity (*g*).

For the practical purpose of finding the acceleration of objects with respect to the Earth, such as for use in an inertial navigation system, a knowledge of local gravity is required. This can be obtained either by calibrating the device at rest,[5] or from a known model of gravity at the approximate current position.

Structure[edit]

Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences an acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to give the acceleration.

In commercial devices, piezoelectric, piezoresistive and capacitive components are commonly used to convert the mechanical motion into an electrical signal. Piezoelectric accelerometers rely on piezoceramics (e.g. lead zirconate titanate) or single crystals (e.g. quartz, tourmaline). They are unmatched in terms of their upper frequency range, low packaged weight and high temperature range. Piezoresistive accelerometers are preferred in high shock applications. Capacitive accelerometers typically use a silicon micro-machined sensing element. Their performance is superior in the low frequency range and they can be operated in servo mode to achieve high stability and linearity.

Modern accelerometers are often small *micro electro-mechanical systems* (MEMS), and are indeed the simplest MEMS devices possible, consisting of little more than a cantilever beam with a proof mass (also known as *seismic mass*). Damping results from the residual gas sealed in the device. As long as the Q-factor is not too low, damping does not result in a lower sensitivity.

Under the influence of external accelerations the proof mass deflects from its neutral position. This deflection is measured in an analog or digital manner. Most commonly, the capacitance between a set of fixed beams and a set of beams attached to the proof mass is measured. This method is simple, reliable, and inexpensive. Integrating piezoresistors in the springs to detect spring deformation, and thus deflection, is a good alternative, although a few more process steps are needed during the fabrication sequence. For very high sensitivities quantum tunneling is also used; this requires a dedicated process making it very expensive. Optical measurement has been demonstrated on laboratory scale.

Another, far less common, type of MEMS-based accelerometer contains a small heater at the bottom of a very small dome, which heats the air inside the dome to cause it to rise. A thermocouple on the dome determines where the heated air reaches the dome and the deflection off the center is a measure of the acceleration applied to the sensor.

Most micromechanical accelerometers operate *in-plane*, that is, they are designed to be sensitive only to a direction in the plane of the die. By integrating two devices perpendicularly on a single die a two-axis accelerometer can be made. By adding another *out-of-plane* device three axes can be measured. Such a combination may have much lower misalignment error than three discrete models combined after packaging.

Micromechanical accelerometers are available in a wide variety of measuring ranges, reaching up to thousands of *g*'s. The designer must make a compromise between sensitivity and the maximum acceleration that can be measured.

Applications[edit]

Engineering[edit]

Accelerometers can be used to measure vehicle acceleration. Accelerometers can be used to measure vibration on cars, machines, buildings, process control systems and safety installations. They can also be used to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity. Applications for accelerometers that measure gravity, wherein an accelerometer is specifically configured for use in gravimetry, are called gravimeters.

Notebook computers equipped with accelerometers can contribute to the *Quake-Catcher Network* (QCN), a BOINC project aimed at scientific research of earthquakes.[6]

Biology[edit]

Accelerometers are also increasingly used in the biological sciences. High frequency recordings of bi-axial[7] or tri-axial acceleration[8] allows the discrimination of behavioral patterns while animals are out of sight. Furthermore, recordings of acceleration allow researchers to quantify the rate at which an animal is expending energy in the wild, by either determination of limb-stroke frequency[9] or measures such as overall dynamic body acceleration[10] Such approaches have mostly been adopted by marine scientists due to an inability to study animals in the wild using visual observations, however an increasing number of terrestrial biologists are adopting similar approaches. This device can be connected to an amplifier to amplify the signal.

Industry[edit]

Main article: Condition monitoring

Accelerometers are also used for machinery health monitoring to report the vibration and its changes in time of shafts at the bearings of rotating equipment such as turbines, pumps,[11] fans,[12] rollers,[13] compressors,[14][15] or bearing fault[16] which, if not attended to promptly, can lead to costly repairs. Accelerometer vibration data allows the user to monitor machines and detect these faults before the rotating equipment fails completely.

Building and structural monitoring[edit]

Accelerometers are used to measure the motion and vibration of a structure that is exposed to dynamic loads.[17] Dynamic loads originate from a variety of sources including:

- Human activities – walking, running, dancing or skipping
- Working machines – inside a building or in the surrounding area
- Construction work – driving piles, demolition, drilling and excavating
- Moving loads on bridges
- Vehicle collisions

Under structural applications, measuring and recording how a structure dynamically responds to these inputs is critical for assessing the safety and viability of a structure. This type of monitoring is called Health Monitoring, which usually involves other types of instruments, such as displacement sensors -Potentiometers, LVDTs, etc.- deformation sensors -Strain Gauges, Extensometers-, load sensors -Load Cells, Piezo-Electric Sensors- among others.

Medical applications[edit]

Zoll's AED Plus uses CPR-D•padz which contain an accelerometer to measure the depth of CPR chest compressions.

Within the last several years, several companies have produced and marketed sports watches for runners that include footpods, containing accelerometers to help determine the speed and distance for the runner wearing the unit.

In Belgium, accelerometer-based step counters are promoted by the government to encourage people to walk a few thousand steps each day.

Herman Digital Trainer uses accelerometers to measure strike force in physical training.[18][19]

It has been suggested to build football helmets with accelerometers in order to measure the impact of head collisions.[20]

Accelerometers have been used to calculate gait parameters, such as stance and swing phase. This kind of sensor can be used to measure or monitor people.[21][22]

Navigation[edit]

Main article: Inertial navigation system

An inertial navigation system is a navigation aid that uses a computer and motion sensors (accelerometers) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. Other terms used to refer to inertial navigation systems or closely related devices include inertial guidance system, inertial reference platform, and many other variations.

An accelerometer alone is unsuitable to determine changes in altitude over distances where the vertical decrease of gravity is significant, such as for aircraft and rockets. In the presence of a gravitational gradient, the calibration and data reduction process is numerically unstable.[23][24]

Transport[edit]

Accelerometers are used to detect apogee in both professional[25] and in amateur[26] rocketry.

Accelerometers are also being used in Intelligent Compaction rollers. Accelerometers are used alongside gyroscopes in inertial navigation systems.[27]

One of the most common uses for MEMS accelerometers is in airbag deployment systems for modern automobiles. In this case the accelerometers are used to detect the rapid negative acceleration of the vehicle to determine when a collision has occurred and the severity of the collision. Another common automotive use is in electronic stability controlsystems, which use a lateral accelerometer to measure cornering forces. The widespread use of accelerometers in the automotive industry has pushed their cost downdramatically.[28] Another automotive application is the monitoring of noise, vibration, and harshness (NVH), conditions that cause discomfort for drivers and passengers and may also be indicators of mechanical faults.

Tilting trains use accelerometers and gyroscopes to calculate the required tilt.[29]

Volcanology[edit]

Modern electronic accelerometers are used in remote sensing devices intended for the monitoring of active volcanoes to detect the motion of magma[30]

Consumer electronics[edit]

Accelerometers are increasingly being incorporated into personal electronic devices to detect the orientation of the device, for example, a display screen.

A *free-fall sensor* (FFS) is an accelerometer used to detect if a system has been dropped and is falling. It can then apply safety measures such as parking the head of a hard disk to prevent a head crash and resulting data loss upon impact. This device is included in the many common computer and consumer electronic products that are produced by a variety of manufacturers. It is also used in some data loggers to monitor handling operations for shipping containers. The length of time in free fall is used to calculate the height of drop and to estimate the shock to the package.

Motion input[edit]

Tri-axis Digital Accelerometer by Kionix, inside Motorola Xoom

Some smartphones, digital audio players and personal digital assistants contain accelerometers for user interface control; often the accelerometer is used to present landscape or portrait views of the device's screen, based on the way the device is being held. Apple has included an accelerometer in every generation of iPhone, iPad, and iPod touch, as well as in every iPod nano since the 4th generation. Along with orientation view adjustment, accelerometers in mobile devices can also be used as pedometers, in conjunction with specialized applications.[31]

Automatic Collision Notification (ACN) systems also use accelerometers in a system to call for help in event of a vehicle crash. Prominent ACN systems include OnStar AACN service, Ford Link's 911 Assist, Toyota's Safety Connect, Lexus Link, or BMW Assist. Many accelerometer-equipped smartphones also have ACN software available for download. ACN systems are activated by detecting crash-strength accelerations.

Accelerometers are used in vehicle Electronic stability control systems to measure the vehicle's actual movement. A computer compares the vehicle's actual movement to the driver's steering and throttle input. The stability control computer can selectively brake individual wheels and/or reduce engine power to minimize the difference between driver input and the vehicle's actual movement. This can help prevent the vehicle from spinning or rolling over.Some pedometers use an accelerometer to more accurately measure the number of steps taken and distance traveled than a mechanical sensor can provide.Nintendo's Wii video game console uses a controller called a Wii Remote that contains a three-axis accelerometer and was designed primarily for motion input. Users also have the option of buying an additional motion-sensitive attachment, the Nunchuk, so that motion input could be recorded from both of the user's hands independently. Is also used on the Nintendo 3DS system.

The Sony PlayStation 3 uses the DualShock 3 remote which uses a three axis accelerometer that can be used to make steering more realistic in racing games, such as *MotorStorm*and *Burnout Paradise*.

The Nokia 5500 sport features a 3D accelerometer that can be accessed from software. It is used for step recognition (counting) in a sport application, and for tap gesture recognition in the user interface. Tap gestures can be used for controlling the music player and the sport application, for example to change to next song by tapping through clothing when the device is in a pocket. Other uses for accelerometer in Nokia phones include Pedometer functionality in Nokia Sports Tracker. Some other devices provide the tilt sensing feature with a cheaper component, which is not a true accelerometer.Sleep phase alarm clocks use accelerometric sensors to detect movement of a sleeper, so that it can wake the person when he/she is not in REM phase, in order to awaken the person more easily.

Orientation sensing [edit]

A number of 21st-century devices use accelerometers to align the screen depending on the direction the device is held (e.g., switching between portrait and landscape modes). Such devices include many tablet PCs and some smartphones and digital cameras. The Amida Simputer, a handheld Linux device launched in 2004, was the first commercial handheld to have a built-in accelerometer. It incorporated many gesture-based interactions using this accelerometer, including page-turning, zoom-in and zoom-out of images, change of portrait to landscape mode, and many simple gesture-based games.

As of January 2009, almost all new mobile phones and digital cameras contain at least a tilt sensor and sometimes an accelerometer for the purpose of auto image rotation, motion-sensitive mini-games, and correcting shake when taking photographs.

Image stabilization[edit]

Camcorders use accelerometers for image stabilization, either by moving optical elements to adjust the light path to the sensor to cancel out unintended motions or digitally shifting the image to smooth out detected motion. Some stills cameras use accelerometers for anti-blur capturing. The camera holds off capturing the image when the camera is moving. When the camera is still (if only for a millisecond, as could be the case for vibration), the image is captured. An example of the application of this technology is the Glogger VS2,[32] a phone application which runs on Symbian based phones with accelerometers such as the Nokia N96. Some digital cameras contain accelerometers to determine the orientation of the photo being taken and also for rotating the current picture when viewing.

Device integrity[edit]

Main article: Active hard-drive protection

Many laptops feature an accelerometer which is used to detect drops. If a drop is detected, the heads of the hard disk are parked to avoid data loss and possible head or disk damage by the ensuing shock.

Gravimetry[edit]

Main article: gravimeter

A **gravimeter** or gravitometer is an instrument used in gravimetry for measuring the local gravitational field. A gravimeter is a type of accelerometer, except that accelerometers are susceptible to all vibrations including noise, that cause oscillatory accelerations. This is counteracted in the gravimeter by integral vibration isolation and signal processing. Though the essential principle of design is the same as in accelerometers, gravimeters are typically designed to be much more sensitive than accelerometers in order to measure very tiny changes within the Earth's gravity, of 1 *g*. In contrast, other accelerometers are often designed to measure 1000 *g* or more, and many perform multi-axial measurements. The constraints on temporal resolution are usually less for gravimeters, so that resolution can be increased by processing the output with a longer "time constant"