We have now reached the final year of your undergraduate program. By now, you would have gone through courses in the fundamental pillars of physics (Classical mechanics, Quantum mechanics, and E&M), and even courses in Thermodynamics/Statistical Physics. Academically, this is where you start taking more advanced courses, even some graduate-level courses. There are plenty of options, depending on where you go to school, how large your physics department is, etc. The choices can range from a class in Solid State Physics, Particle Physics, advanced laboratory work, etc. If you already have a clear set of interests and know what area of physics you would like to end up in, then this is where you want to try to enroll in a class in that area. But even if you don't know for sure yet (and this tends to be the case for most students), it is still valuable to enroll in one of these "specialized" areas of physics, even if you may not eventually go into that field.The start of your senior year requires that you do some serious thought on what you wish to do upon graduation. Most physics majors will go on to graduate school with the hope of obtaining their doctorate. So in this part of the series, we will concentrate on the application process of going to graduate school. If this is the path you intend to take, then you need to prepare yourself in several ways:1. Prepare to take your Graduate Record Examination (GRE). This should include both the GRE General and GRE Subject Test. While the GRE scores may not be required for admission application in many schools, they are usually required if you are seeking any form of assistantship. So it is best if you already have the test scores.2. Apply to graduate schools EARLY! If you intend to enroll in the Fall, you should have ALL your applications in by December of the previous year, especially if you are seeking an assistantship. In many highly competitive schools, your applications may need to be in even earlier. It is NEVER too early.3. Unless you have a 4.0 GPA, have outstanding letters of recommendation, and are the son of the President of the United States, you have some uncertainty if your first choice of school will accept you. It is ALWAYS recommended that you group the schools you are applying to into 3 categories: (i) Top-tier schools that you know are very difficult to get into (ii) Middle tier schools that you may have a chance to get in and (iii) lower-tier schools that you think you can get in. Note that these do not have any reflection on the QUALITY of instructions/programs at each school. In many instances, it is only the "perceived" prestige that makes one school more "desirable" than the other.4. Do as much research on each school that you are applying to. If you know of some program or research area that a school is good in that you are also interested in, then look it up and try to find the latest publications in physics journals. Your admission application usually requires that you write an essay regarding your aims, ambitions, and why you would want to study there. So it is always good to be specific, and not just give some generic description. Mention things specific to that school and that physics program and why you want to be involved in that. It is extremely important if you can also show a previous interest or work in a similar area. This will tell the admission officer that you are a candidate who can be beneficial to them. Note that saying such a thing in your application typically does NOT commit you to that particular area of physics. You can still change your mind later on if you wish. So don't hold back on the enthusiasm.5. This last part is a bit dicey since the situation can either turn out very positive or very bad. If you feel confident enough in your ability, you may want to contact directly a faculty member of the school that you would like to attend. This would be a highly competitive school. You want to do this in cases where you think direct communication may enhance your chances – so don't do this if you think your contact may backfire. The best way to do this is to see if any of the faculty members of your undergraduate institution know of anyone there personally. It is always best to have such a recommendation. If you do decide on such contact, tell the person why, your interest, and that you would be interested in working in his/her research group, etc.In the next installment, I will try to describe what you can expect graduate school to be BEFORE you get there.Next Chapter: What to Expect from Graduate School Before You Get There Questions or comments on this article? E-mail us at feedback@sciencenews.org | Reprints FAQ A version of this article appears in the May 1, 2025 issue of Science News. When I ask questions about the conservation of information I frequently get the reply, "It depends on what you mean by information."   So, I researched how to better define information. What I found is almost more interesting than the conservation question. That sounds like the makings of a fun PF Insight article, so here goes.This article is a survey of information and information-conservation topics in physics. It is intended for an amateur physics audience. To make this article suitable for all levels of readers, most of my references are to Professor Leonard Susskind's video courses, or to Wikipedia.Start SimpleIn both his Classical Mechanics[i] and Statistical Mechanics[ii] courses, Susskind begins with simple examples of the allowable laws of physics. Consider a system with 6 possible states, A-F. We are interested in the allowable rules of how the system can evolve. In the blue example below, A goes to B. B to C, C to D, D to E, E to F, F to A, or ABCDEF overall. The yellow example is more complex with cycles ABF CE and D, but they are still allowable. Allowable rules are deterministic, time reversible[iii], and they conserve information.   For each of those allowable laws, we could write corresponding equations of motion. What is the information conserved? At any stage, we can calculate how we got there (the past) and where we'll go next (the future), and which cycle (such as yellow ABF) we belong to.The red example, has two arrows coming out of A, and C has two arrows coming in. Those are not deterministic, not time-reversible, and do not conserve information, and thus are not allowed.Next, consider a 6-sided die.   The die has 6 microstates. Let's define I to be the information in this system or the number of microstates. What do we know about the die's position? Maximum knowledge K occurs when we know exactly which side is up. Minimum knowledge occurs when we have no idea about the position. We can define entropy E, as being proportional to our uncertainty about the position. Because of the way we defined I and E, then we can say trivially that K=I-E or I=K+E. I should add that K could also be called "knowability" or "observability" just to emphasize that there is no need for an intelligent being in physics.First off, we have to be clear about the rather strange way in which, in this theory, the word "information" is used; for it has a special sense which, among other things, must not be confused at all with meaning. It is surprising, but true, from the present viewpoint, two messages, one heavily loaded with meaning, and the other pure nonsense, can be equivalent as regards information. — Warren Weaver, The Mathematics of Communication, 1949 Scientific American.Those definitions of entropy and that relationship cannot be applied literally in other physics contexts, but they are nevertheless useful as we will see in other contexts. However, there is a familiar everyday life analogy.   A 1TB hard drive can store 1TB of information, but when it is new or freshly erased, it contains near-zero knowledge.Consider 4 gas molecules in a box. [I chose the small number 4, to avoid thermodynamics definitions.] The number of possible microstates is proportional to the number of molecules. If the 4 molecules were bunched in one corner then we have better knowledge of their positions than if they are distributed throughout the box. The point is that entropy (and thus knowledge) can vary with the state of the system, whereas the number of microstates (information) does not vary with state.That leads me to definitions that we can use in the remainder of this article.
"Knowledge and Entropy are properties of the system and the state of the system (and possibly external factors too). Information is a property of the system and independent of the state.[iv]" In my opinion, lack of attention to that distinction between information and knowledge is the origin of many misunderstandings regarding information in physics.Microstates, Macrostates, and ThermodynamicsA definition of information consistent with our simple cases is "the number of microstates." Susskind says[v] that the conservation of information could also be described as the conservation of distinction. Distinct states never evolve into more or fewer distinct states.In thermodynamics, a process can be reversible or irreversible. In thermodynamics, we also have the famous 2nd Law. However, thermodynamics uses macroscopic quantities including temperature. But, in this article, we are discussing microstates, not macrostates, so some thermodynamic concepts and definitions do not apply.Notwithstanding the above, I can't resist mentioning that in Boltzmann's definition[vi], entropy is "a measure of the number of possible microscopic states (or microstates) of a system in thermodynamic equilibrium, consistent with its macroscopic thermodynamic properties (or macrostate)."   It then follows that the total number of microstates (information) is greater than or equal to the entropy. For the case with exactly one macrostate, then entropy and information are equal.   That is consistent with information as being independent of the (macro)state.An amusing aside. Susskind calls[vii] Conservation of Information the -1st law of thermodynamics, and the 0th law of thermodynamics is, "If A is in thermal equilibrium with B, and B with C, then A must be in thermal equilibrium with C", and the more familiar 1st law that we teach students is Conservation of Energy.   He emphasizes that information is more fundamental than entropy and energy.Information in Classical MechanicsIn classical mechanics we learn of phase space; meaning the multidimensional space formed by position x and momentum p degrees of freedom. In A below, we see a depiction of phase space (showing on only one x and one p axis). Each distinct point can be considered a possible microstate as in A. In time, the states can evolve to other places in phase space, as in B. But the trajectories never fork, and never converge (as in C), thus conserving the number of distinct microstates. A, B, and C are the continuous analogs of the discrete evolutions (blue, yellow, and red boxes) we started with above.Even better, Liouville's Theorem[viii] says that if we choose a region in phase space (see D above); it evolves in time to different positions and shapes, but it conserves the volume in phase hyperspace.   Liouville's Theorem is often said to express the conservation of information in classical mechanics.   Referring to the little picture on the right, drawing the boundaries of the volume determines the system, and thus the information.   The shape of the boundary (state) evolves with time. Evolution can be ordered or chaotic.Is entropy conserved too? In general, no. (again system↔information state↔entropy) However, if we fork the definition of entropy to include coarse versus fine grained entropy, that leads to an interesting side topic.In classical mechanics, we should also consult with "the most beautiful idea in physics", Noether's Theorem. That is the theorem that says that every differentiable symmetry of the action of a physical system has a corresponding conservation law.It would be nice to use Noether's Theorem to prove a relationship between information conservation and some symmetry of nature.   I found one source that says that Noether's Theorem proves that information conservation is a result of time reversal symmetry[ix].   Another source says that it is not[x].Alas, time reversal is discrete and non-differentiable, so that won't work. How about some other symmetry?   If ##I ## represents the quantity of information, and if we wish to prove that ##\frac{dI}{dt}=0## using the Principle of Least Action, then the quantity of information ##I ## should appear in the expression for the action. As far as I know, it does not.   So, it seems that we can't use Noether's Theorem to prove information conservation.Information in Quantum MechanicsUnitarity is one of the postulates of Quantum Mechanics[xi]. Unitarity is also said to be the foundation of the conservation of information. (By the way, I exclude from this discussion all interpretations of quantum mechanics.)Unitarity is also said to conserve probability. Huh? So now information is probabilities?   These Wikipedia sources[xii] say yes, conservation of probabilities implies conservation of information.In another context[xiii], Susskind said that if quantum evolutions were not unitary, the universe would wink out of existence.   I believe that what he was referring to is this. If evolutions were sub-unitary, then the probabilities would shrink at each time evolution, until only one microstate remained for the entire universe. If they were super-unitary, the probabilities would increase with each evolution to the point where the identity of particles would be smeared to oblivion. In either case, the universe as we know it could not exist. I interpret all that as saying that the number of microstates (hence information) is conserved in quantum evolution. One might also say it as the system is conserved while the state of the system evolves.Here's another example. Consider a system of two free electrons. Electrons are spin ½ particles, and we can know their spins because there is an observable for a spin. Now consider what happens if the two electrons become fully entangled in the singlet pair state which is spin 0. There is no observable for the singlet to return the spins of the component electrons. This is a time of evolution where information is conserved, but knowledge (or knowability) is not conserved. The state changed, but the system remained the same.   Remember also that the electrons can also become disentangled thus restoring the original knowledge, while the information of the two-electron system remains invariant throughout.This example illustrates why I prefer to define information and knowledge as distinct things.By the way, there is also a quantum version of Liouville's Theorem[xiv] that says (guess what) quantum information is conserved.Information in Cosmology & General RelativityConservation of information at the origin of the universe is the question that first interested me in this topic. I never found an answer to that, and probably never will.None of Special Relativity, General Relativity, or Cosmology directly address information. However, there is a red-hot issue; the so-called Black Hole Information Paradox[xv].Stephen [Hawking] claimed that "information is lost in black hole evaporation," and, worse, he seemed to prove it. If that was true, Gerard ['t Hooft] and I realized, the foundations of our subject were destroyed. —Leonard Susskind[xvi]By the way, the Wikipedia article about the paradox offers yet another definition for information conservation.There are two main principles in play:Quantum determinism means that given a present wave function, its future changes are uniquely determined by the evolution operator.Reversibility refers to the fact that the evolution operator has an inverse, meaning that the past wave functions are similarly unique.The combination of the two means that information must always be preserved.This so-called black hole paradox was also the topic of at least 15 PF threads. In my opinion, many of those discussions were spoiled because participants argued about information with differing definitions of the word information in their heads. Nevertheless, the debate continues at levels far above my head.   The Wikipedia article summarizes the latest arguments for and against.   It also points to another interesting related side topic, The Holographic Principle, which in turn leads to The Limit on information density which leads to The Bekenstein Bound which also talks about limits on information density. Does all this make you feel that you are falling into the rabbit hole? I feel that way.By the way, I'm delighted that The Bekenstein Bound provides the only example I know of an equation relating information in bits to ordinary physical quantities.##H ≤ \frac{2\pi cRM}{\hbar ln 2} ≃ 2.5769082 \times 10^{43} \frac{bits}{kg\cdot m}\cdot M \cdot R##Where H is the Shannon entropy, M is mass in kg, and R is the radius in m of a system.UtilityLaymen frequently hold the false impression that the purpose of science is the discovery of truth.   Scientists are more interested in what is useful, and less interested in the truth. Truth can be very philosophical, but usefulness is proved by use.Unfortunately in physics, information is more interesting than it is useful. If ##I## represents a quantity of information measured in bits (or qubits), how do we calculate it? How do we measure it? I don't know exactly how many bits it takes to completely describe a photon, or a nucleus, or a lump of coal. The lack of ability to define and measure a numerical quantity for information prevents me from using information with The Principle of Least Action, or doing a before-after information balance on an event such as beta decay.In a beta decay event, a neutron decays into a proton ##p##, an electron ##e^-##, and an electron antineutrino ##\bar{u}_e##. We know that momentum, energy, and information should all be conserved. Therefore, we can write a momentum balance equation or an energy balance equation, but how about an information balance equation? Suppose we have a function ##I()## that returns the quantity of information of a particle. We should be able to write ##I(n)=I(p)+I(e^-)+I(\bar{u}_e)##.   Since ##I()## should always be nonzero positive, it also seems conclusive that the information in a neutron must be greater than the information in a proton. But we have no such function I(n).   We can't say how much information is in a neutron, yet we can write equations relating I(n) to other information. Hence, my complaint about the information's lack of utility.Information and CausalityCausality is a fundamental principle in physics.   There is no theory of causality, nor is it derived from other laws.   Causality never appears explicitly in equations. Yet if causality was violated, physics and the universe would be thrown into chaos.Conservation of Information (COI) is a fundamental principle in physics.   There is no theory of COI, nor is it derived from other laws. COI never appears explicitly in equations. Yet if COI was violated, physics and the universe would be thrown into chaos.Yet the following subjective statements are also true. "Causality means that the cause comes before the effect," is instantly understood and accepted by almost everyone. "COI means that information is never created or destroyed.," is instantly misunderstood and challenged by almost everyone.ConclusionLet's summarize. In physics, the word information is closely related to microstates and probabilities. In some limited circumstances information is equal to entropy, but in most cases not.   Information should never be confused with knowledge despite what natural language and the dictionary say. And never confused with the knowledge of intelligent beings. Despite our inability to quantify information, conservation of information seems firmly established in many contexts. Limits to information density also appear to be well-founded, again despite our inability to quantify it.   Information in physics has tantalizing parallels with Shannon Information Theory in communications and computer software, but it is not identical.On PF, we frequently remind members that energy does not exist by itself in space; energy is a property of fields and particles. Should we say the same thing about information, that it is a property of fields and particles? Some people invert that view and speculate that information is the building block on which fields particles and even reality are built[xvii]. A third view is that there is no such thing as information as a physical quantity, it is just a lingual artifact of our way of speaking.   This article brings no clarity to those questions. All we have is hand waving. I blame that on less-than-useful definitions.The above notwithstanding, the future sounds bright. Professor Susskind has been touring the country with a series of lectures including ER=EPR in the title[xviii]. He is discussing the research direction of his Stanford Institute for Theoretical Physics.   He said that they are looking toward information theory to unite quantum mechanics with general relativity.   Of course, it remains to be seen if they will succeed. If they do, Nobel Prizes will surely follow.   But for me, their success would hopefully produce one thing even more welcome; namely, a more useful quantitative definition of the word information.A postscript. Just as I was wrapping up this article, I stumbled across another Susskind quote[xix] that turned everything on its head.When a physicist, particularly physicists of my particular interest, talks about quantum information, they are usually talking about entanglement. Leonard Susskind.Ay ay ay; I have a headache.What is your definition of information in physics? Please contribute it to the discussion thread. But no QM interpretations, please. Also, quantitative definitions please; not examples. Finally, please remember that a bit is a unit, not a definition.Thanks to member @Dale for his helpful suggestions.References:[i] Susskind, Classical Mechanics, Lecture 1[ii] Susskind, Statistical Mechanics, Lecture 1[iii] In thermodynamics we have both reversible and irreversible processes. Information depends on microstates. Thermodynamics depends on macrostates, so it does not apply here.[iv] Susskind, Statistical Mechanics, Lecture 1[v] Susskind, Classical Mechanics, Lecture 5[vi] Wikipedia: Boltzmann's principle[vii] Susskind, Statistical Mechanics, Lecture 1[viii] Wikipedia: Liouville's theorem (Hamiltonian)[ix] PBS Space Time Why Quantum Information is Never Destroyed[x] Wikipedia: Symmetry (physics)[xi] Wikipedia: Mathematical formulation of quantum mechanics[xii] Wikipedia: Probability Current, Continuity Equation[xiii] Susskind Book: The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics[xiv] Wikipdeia: Quantum Liouville equation, Quantum Liouville", Moyal's equation, Quantum Liouville equation[xv] Wikipedia: Black Hole Information Paradox[xvi] Susskind Book: The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics, page 21.[xvii] Scientific American: Why information can't be the basis of reality[xviii] This Youtube search, returns 3,480 hits on ER=EPR. ER refers to Einstein-Rosen bridge or wormhole, a solution of General Relativity. EPR refers to the Einstein–Podolsky–Rosen paradox regarding quantum entanglement. So ER=EPR is a clever way to suggest the unification of GR and QM.[xix] Susskind: ER=EPR but Entanglement is Not Enough Skip to content Sign up for our newsletter We summarize the week's scientific breakthroughs every Thursday. Questions or comments on this article? E-mail us at feedback@sciencenews.org | Reprints FAQ A version of this article appears in the June 1, 2025 issue of Science News. R. Dahn. Demythologizing quantum history. Physics Today. Vol. 78, April 1, 2025, p. 38. doi: 10.1063/pt.assl.oxzd. Google Quantum AI and collaborators. Quantum error correction below the surface code threshold. Nature. Vol. 638, December 9, 2024, p. 920. doi: 10.1038/s41586-024-08449-y. A. Lodesani et al. Weak magnetic field effects in biology are measurable—accelerated Xenopus embryogenesis in the absence of the geomagnetic field. bioRxiv.org October 16, 2024. doi: 10.1101/2024.10.10.617626. M. Bild et al. Schrödinger cat states of a 16-microgram mechanical oscillator. Science. Vol. 380, April 21, 2023, p. 274. doi: 10.1126/science.adf7553. I.H. Deutsch. Harnessing the power of the second quantum revolution. PRX Quantum. Published online November 13, 2020. doi: 10.1103/PRXQuantum.1.020101. C. Marletto and V. Vedral. Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity. Physical Review Letters. Vol. 119, December 15, 2017, 240402. doi: 10.1103/PhysRevLett.119.240402. Questions or comments on this article? E-mail us at feedback@sciencenews.org | Reprints FAQ A version of this article appears in the June 1, 2025 issue of Science News. Questions or comments on this article? E-mail us at feedback@sciencenews.org | Reprints FAQ This story was updated on February 11, 2025, to correct the description of Heisenberg's uncertainty principle. In the classical Newtonian theory of gravity, the shell theorem holds. ( )
In the beginning of the derivation of the Schwarzschild solution, the spherically symmetric object is replaced by a point mass. The proof that this can be done in curved space-time is missing. If the proof of this statement were to use the Schwarzschild solution directly or indirectly, it would not be logically valid. It would be so called "circular reasoning". Is there... By Bosko Monday, 2:02 PM Replies: 34 One of the most enduring mysteries of particle physics may be finally resolved, two new studies suggest. The oddities of muons, subatomic particles that are relatives of electrons, are starting to make sense. Muons have an internal magnetism that scientists have struggled to pin down: Measurements of a magnetic quirk of the particles have long clashed with theoretical predictions. Now, scientists report the most precise measurement yet of that property, the anomalous magnetic moment of the muon, which tweaks the strength of muons' internal magnets. Meanwhile, a team of physicists updated their theoretical prediction of that tweak based on the standard model, the highly successful theory that describes subatomic particles and their interactions. That prediction shifted from the previous estimate, erasing the longstanding discrepancy. "That's another triumph of the standard model," says Bhupal Dev of Washington University in St. Louis, who was not involved with the two studies. Sign up for our newsletter We summarize the week's scientific breakthroughs every Thursday. It's a bittersweet development for physicists like Dev who search for cracks in the stalwart standard model in hopes of finding another theory that will supplant it. The disagreement between measurements and predictions has inspired perhaps hundreds of papers, many proposing new theories purporting to explain the mismatch, Dev says. Those theories are now nixed, dashing the hopes of the physicists who created them. The frenzy began nearly 25 years ago, when the first hints of the discrepancy appeared in an experiment at Brookhaven National Laboratory in Upton, N.Y. Now, Dev says, "it's finally coming to a close." Muons' magnetism causes them to wobble when traveling through a magnetic field. The Muon g−2 experiment (pronounced "g minus two", the term used in equations to represent the anomalous magnetic moment) measured the rate of these wobbles in a giant, doughnut-shaped magnet, revealing the anomalous magnetic moment. The new measurement has an uncertainty of just 127 parts per billion or about 13 millionths of a percent. "It's one of the most precise measurements that humans have ever made about our fundamental world," says theoretical physicist Tom Blum of the University of Connecticut in Storrs, who was not involved with the measurement. The experiment's precision surpassed what the scientists had planned to achieve, researchers reported June 3 in a paper posted at the experiment's website and during a scientific seminar at Fermilab, in Batavia, Ill., where the experiment is located. "We have done it," says Muon g−2 collaborator Thomas Teubner, a theoretical physicist at the University of Liverpool in England. The result was consistent with previous measurements of the muon's anomalous magnetic moment. But "from the theory side… things have changed dramatically," says Blum, a member of the Muon g−2 Theory Initiative, which compiled the theoretical prediction. New developments have brought that prediction in line with experimental measurements, the group reports in a paper submitted May 27 at arXiv.org. The shift comes from one particularly challenging bit of the calculation. That piece of the calculation accounts for an effect called hadronic vacuum polarization. To fill in that piece of the puzzle, scientists previously relied on experimental data as an input to the calculation, collected from a variety of experiments involving electrons colliding with their antimatter counterparts, positrons. But a recent experiment called CMD-3, at the VEPP-2000 particle collider in Novosibirsk, Russia, threw a wrench in that data-driven strategy when it disagreed with older experiments. That meant that the data wasn't understood well enough to use as an input to the calculation. As an alternative, researchers have now calculated the hadronic vacuum polarization term from scratch, without input data, using a technique called lattice quantum chromodynamics. The technique is based on the theory of quantum chromodynamics, which describes the business of quarks and gluons, subatomic constituents of protons, neutrons and other particles. In order to make the complex calculations possible, lattice QCD calculations break space and time up into a grid and typically employ powerful supercomputers. Importantly, when the lattice QCD value is used for the tricky part of the calculation of the muon anomalous magnetic moment, the prediction matches the experimental measurement, and the conundrum is resolved. The newfound results don't quite wrap everything up in a neat little bow, however. Scientists still don't understand why the CMD-3 experiment's results don't match older experiments. Now, physicists aim to refine the prediction, both by working to resolve that discrepancy and by improving the lattice QCD calculations. "This is a very urgent thing that the community is taking seriously," says theoretical physicist Aida El-Khadra of the University of Illinois Urbana-Champaign, a leader of the Muon g−2 Theory Initiative. The development highlights the growing impact of lattice QCD. The technique has unlocked a wide variety of particle physics calculations, such as determining where protons' mass comes from. The muon g−2 calculation is another success for the technique. "This is a step in a path in a well-established garden of results," El-Khadra says. Now, the lattice QCD garden is in full bloom.
In sports, the best offense is often a good defense. It's not clear if the same applies in nuclear war. In the face of nuclear threats from adversaries like Russia, China and North Korea, some politicians are clamoring for a system to reliably protect the United States from incoming missiles. That's the aim of President Donald Trump's plan for a next-generation missile defense system, dubbed the "Golden Dome." Trump announced on May 20 that an architecture had been selected and that the system would be operational before the end of his term, at a cost of $175 billion. But some scientists suggest that implementing such a system, as called for by a January executive order, would be daunting. Sign up for our newsletter We summarize the week's scientific breakthroughs every Thursday. The United States already maintains a nationwide missile defense system aimed at defending against a small-scale attack from intercontinental ballistic missiles, or ICBMs, launched by a rogue nation such as North Korea. But a February report from the American Physical Society concludes that defense against even a small-scale attack is uncertain. And the system's capabilities are likely to remain relatively limited within the next 15 years, the report argues. The Golden Dome initiative aims to protect the country from more capable adversaries such as Russia and China — a more difficult task. "Intercepting even a single, nuclear-armed intercontinental-range ballistic missile or its warheads ... is extremely challenging," physicist Frederick Lamb of the University of Illinois Urbana-Champaign, chair of the group that produced the report, said at an APS meeting in Anaheim, Calif. in March. "The ability of any missile defense system to do this reliably has not been demonstrated." And as countries come up with new types of weapons that could skirt defenses, the situation is getting even more challenging. Golden Dome aims to defend against not just ICBMs, but also hypersonic weapons, advanced cruise missiles and more. And Golden Dome would take missile defense to space. In addition to ground-based systems, Golden Dome would use potentially thousands of defensive weapons called interceptors orbiting Earth, poised to neutralize attacks. Golden Dome has drawn praise from missile defense proponents. "The initiative to elevate and prioritize air and missile defense … that's long overdue and it's entirely appropriate," says Tom Karako, director of the Missile Defense Project at the Center for Strategic and International Studies in Washington, D.C. Lower launch costs, proponents argue, make space-based missile defense more realistic than in the past. "I think we're a lot closer than people recognize," says nuclear deterrence and missile defense expert Robert Peters at the Heritage Foundation in Washington, D.C. The U.S. Missile Defense Agency disputed the claims of the APS study, arguing that it relied on older data and unclassified reports that don't reflect recent improvements and upgrades to the missile defense architecture. "MDA's Missile Defense System stands ready and fully capable of defending the United States, deployed forces and allies from a rogue nation's missile attack," the agency said in a statement. But critics note that the difficulty of the problem remains. "Technology has advanced tremendously," says Victoria Samson of the Secure World Foundation in Washington, D.C. "But the laws of physics have not changed, and that's really what the challenge is." ICBMs are a formidable target. An ICBM launches in a giant arc that sends the weapon it carries careening through space, traversing more than 5,000 kilometers to reach its target. The challenge of intercepting them has been compared to hitting a bullet with a bullet. But this understates the problem: At around 25,000 kilometers per hour, ICBMs speeds are about seven times that of a bullet. What's more, they're generally armed with nuclear warheads, each capable of killing a million people, rather than one. ICBMs have three phases of flight, and there are different possibilities for intercepting the missiles during each phase. In the boost phase, which lasts a few minutes, rocket engines lift the missile to high altitude and high speeds. In the midcourse phase, the engines are jettisoned. The missile enters space, releasing one or more warheads, which continue upward before falling back down again. This part of the trajectory, in which the warheads are moving in an arc under the influence of gravity alone, is what's known as ballistic motion — hence the missiles' name. That phase lasts around 20 minutes. An ICBM goes through three main stages of flight (illustrated, not to scale). In the boost phase, the ICBM is launched and a rocket lifts it into a trajectory in space (red path). In the longest phase, midcourse, the warheads are released, traveling in an arc under the force of gravity. In the terminal phase, the weapon reenters the atmosphere. Interceptors could use different techniques to disable it in each stage. APSAPS The terminal phase is the shortest: The warhead reenters the atmosphere, descending to its target in under a minute. This phase is so short that the only possibility for stopping a weapon is by placing interceptors very close to the point of impact. Such tactics can be used as one layer of missile defense, a back-up protection for sensitive areas like military bases, but it's not practical for protecting a large country. So concepts for protecting the entire United States typically focus on the boost phase or the midcourse phase. The midcourse phase is the bread-and-butter of the country's current missile defense system. Forty-four interceptors in Alaska and California aim to intercept incoming missiles in space. That system — which by some estimates has cost over $60 billion — is known as ground-based midcourse defense. It's aimed at defending the United States against a small number of unsophisticated missiles from North Korea or another rogue nation. Critics note that this system has been about 60 percent effective in tests. However, that statistic includes tests going back over 25 years. The tests performed in more recent years have been more successful. "Any time you test a new system, there are going to be failures early on," Peters says. "That's how you learn what works." An interceptor is launched from Vandenberg Space Force Base, Calif., during testing of a ground-based midcourse missile defense system on December 11, 2023.U.S. Missile Defense Agency Another complaint is that its tests aren't realistic, but proponents say it's not possible to fully re-create realistic conditions. "We have not had North Korea try to nuke the continental U.S. yet, so … it's not an actual battle test," Peters says. He points to real-world uses of missile defense in conflicts in Ukraine and Israel. "We've been really effective with those tests in real-world operation environments." However, none of the weapons shot down in those conflicts were ICBMs. "One should not mix apples and oranges," says physicist and aeronautics engineer Paul Dimotakis of Caltech, who was not involved with the APS report. "Different types of attacking missiles and their number and sophistication will require different tailored defenses." And there's one particularly thorny snag to missile defense in the midcourse phase: countermeasures. An adversary could release debris or decoys along with a real warhead, for example, thwarting attempts to intercept it. "One key reason why the midcourse phase is difficult is because you're in space, and different objects of different mass travel exactly the same," says physicist James Wells of the University of Michigan in Ann Arbor, a coauthor of the APS report. The lack of air in space means that a warhead will travel at the same speed as a balloon designed to mimic it, making them hard to distinguish. That can make the concept of reliable missile defense in the midcourse phase a bigger task than it otherwise seems. "People say, 'We got to the moon, why can't we do this?' Well, the moon didn't suddenly move out of the way," Lamb said at the APS meeting. "It's a huge technical challenge to identify what the target is.... That's been the bugaboo of midcourse intercept from the very beginning." The trickster tactics of the midcourse phase aren't possible in the boost phase, during which the warheads remain within the missile, and the entire package travels through the atmosphere. "There's this perennial dream of intercepting in the boost phase," Wells says. But because the boost phase lasts only a few minutes, "that time pressure is enormous to get an interceptor there." Boost phase is over so quickly that any interceptor would need to be positioned very close to the launch site. And for a large country with an inaccessible interior, like Russia or China, that's a no-go — on Earth's surface, at least. Interceptors in low Earth orbit — at altitude of 2,000 kilometers or less — could do it. But those interceptors would be orbiting, rather than parked over the country of interest. To be certain of taking down a missile, a large constellation of satellites would be needed. And to protect the United States from salvos of multiple missiles at once, the number of satellites would have to increase further. Ensuring protection from just one North Korean ICBM would require more than 1,000 interceptors in orbit, the APS report finds. Protection from 10 might demand over 30,000 interceptors, depending on missile type and other assumptions. For comparison, there are about 12,000 active satellites in orbit around Earth, most in SpaceX's Starlink network. A constellation of 1,600 space-based interceptors (illustrated) would be needed to intercept just four North Korean ICBMs launched simultaneously, according to an American Physical Society report.APS 2025, adapted from NRC 2012 Golden Dome aims to protect not just from North Korea but also from attacks by more capable adversaries, such as Russia and China, who together have hundreds of ICBMs. But Golden Dome is not intended to be impenetrable, Peters says. "I don't know anyone who is credibly making that argument." Instead, Peters says, it would prevent a small-scale attack, with a few low-yield nuclear weapons. To thwart Golden Dome, the idea is that an adversary would need to launch a substantial barrage — one certain to provoke a massive nuclear war. It's unclear how many ICBMs Golden Dome would aim to neutralize and how many satellites would be needed. But even for small-scale attacks, defending from Russia and China would demand more satellites simply to cover a wider geographic area than needed for North Korea alone. "It really is an enormously huge difference to be defending against a small region [versus] a large continent," says astrodynamicist Thomas González Roberts of Georgia Tech in Atlanta. Depending on the specific objectives, Golden Dome could require an untenable number of satellites, he says. "I would call a lot of these proposals infeasible, but in reality, we don't know what these proposals are really asking," Roberts says. Without specific goals for the numbers of ICBMs to be intercepted, from which countries, it's unclear how plausible the plan is. Trump shared few specifics in the May 20 news conference, saying "Golden Dome will be capable of intercepting missiles even if they are launched from other sides of the world and even if they are launched from space." That, Roberts says, suggests an extensive system. "You would be hard-pressed to find a system that could do that for $175 [billion]. Even the most optimistic assumptions behind boost-phase missile defense would suggest that that is impossible." What's more, Roberts says, to do it in three years would require a faster launch cadence than ever before. The price tag is bound to be a thorny issue. Already, over the past 70 years, the United States has spent more than $400 billion on missile defense, according to the APS report. The budget bill that is currently working its way through Congress would lay out $25 billion for Golden Dome in fiscal year 2025. And a May 5 Congressional Budget Office report suggests that, even with lower launch costs, the space-based effort alone would cost between $161 billion and $542 billion over a period of 20 years. "It's really complicated," Samson says. "It's like a bumper sticker type thing. It's easy to say … 'Do you want to be defended against ballistic missiles?' And everyone says, 'Yes, of course, I'd love to.' Great, but here's all the things you need to look at."