The Science Behind the Art of Making Mounts

for Antiquities and other Art Objects in Earthquake Country

Vincent Avalos,
Mountmaker

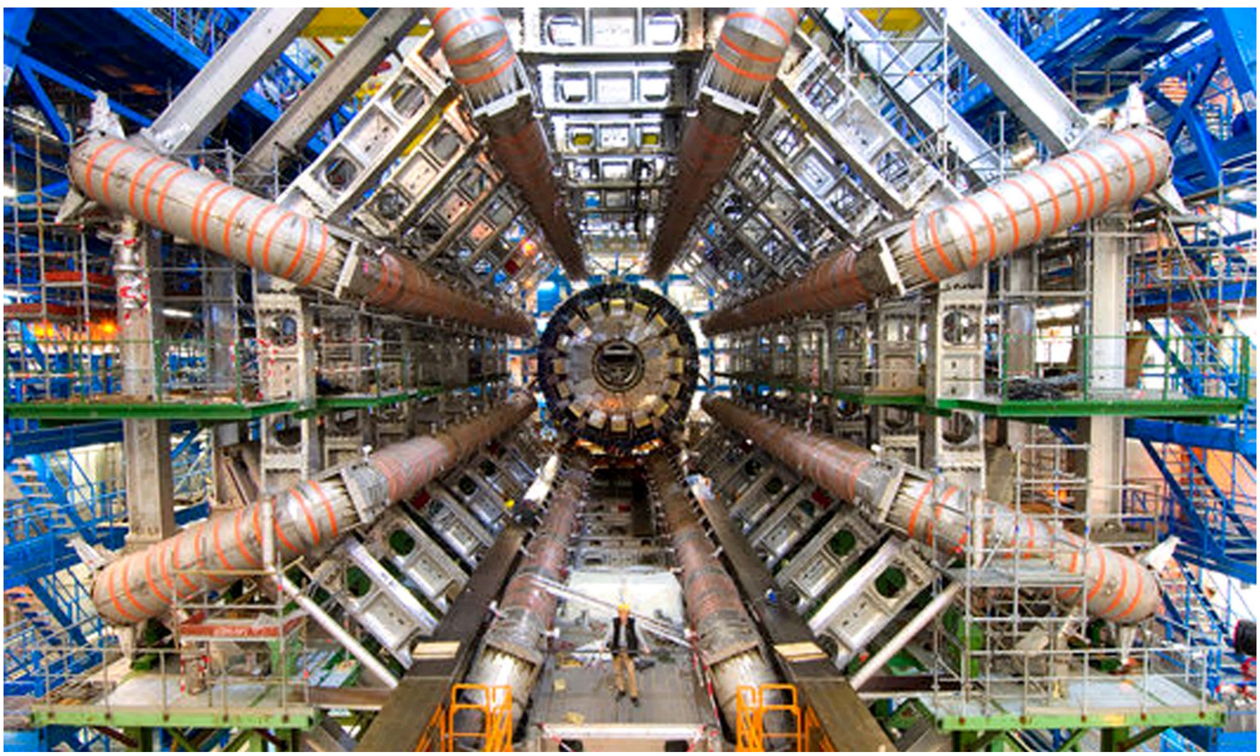
ASIAN ART MUSEUM

Mountmakers create discreet display armatures to exhibit sculpture and other artifacts for collectors and the general public. This is similar to the way a jeweler mounts a gem. In doing so we are often asked to defy gravity. Behind walls and under floors the recondite arts of mountmakers bring to life our art, curios and antiquities.

Defying gravity is actually the easy part; mitigating forces coming from all the other directions in space and time such as those generated by the occasional earthquake can prove to be even more challenging.

Here is a brief introduction to seismology and some of the basic laws of physics as they apply to mountmaking in earthquake zones. This paper will I hope provide (in a preliminary way) a means of using this information to create mounts that will effectively withstand a likely seismic event.

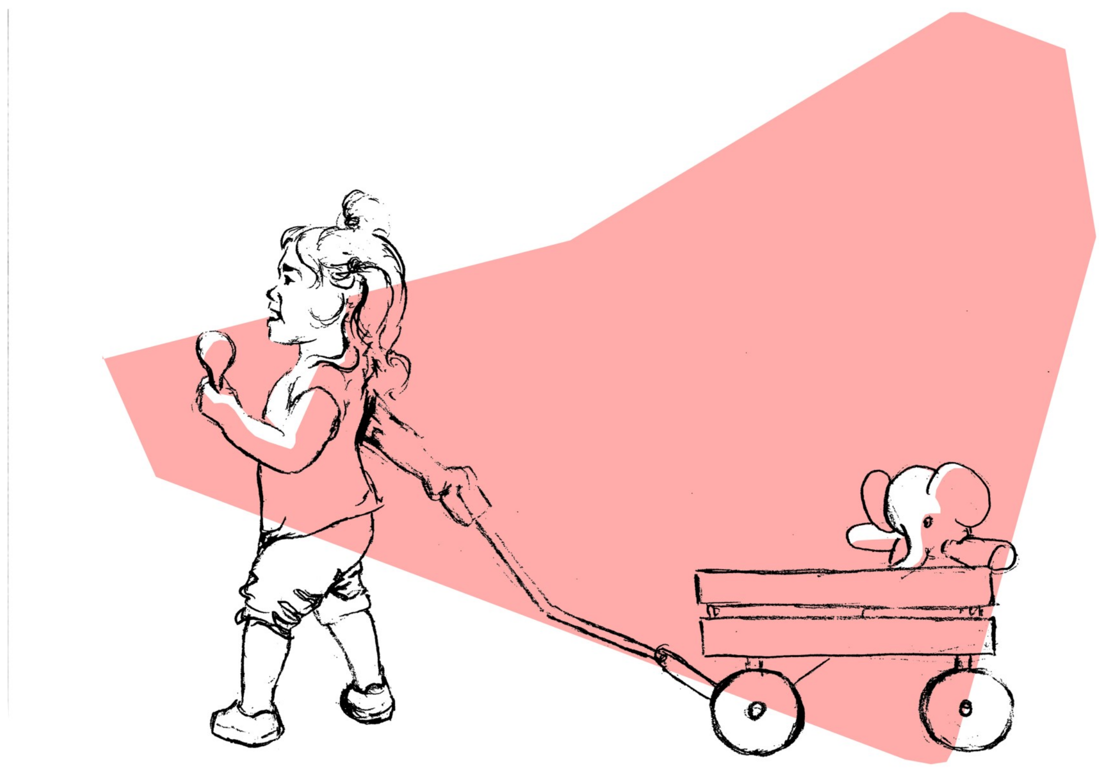

When we speak of the interactions of objects in the daily world, of the physicality of the world, or the amount of “stuff” in something, we are talking about what physicists call mass. It seems mundane enough yet we are giving our best minds billions of dollars to build experimental evidence that can describe what “mass” actually is.



Mass defies explanation. It is easy to end up talking in circles when trying to define it. Mass is not simply the weight of something or the pressure or force of something. These are just measurements but the measurement is not itself mass. We describe mass in one of two ways and upon closer inspection we find that they are actually the same thing. We say that there is inertial mass and gravitational mass. Their relationship is called the equivalency principle, which for our purposes is what we will focus on. We will leave the detector at CERN to come up with a deeper explanation.

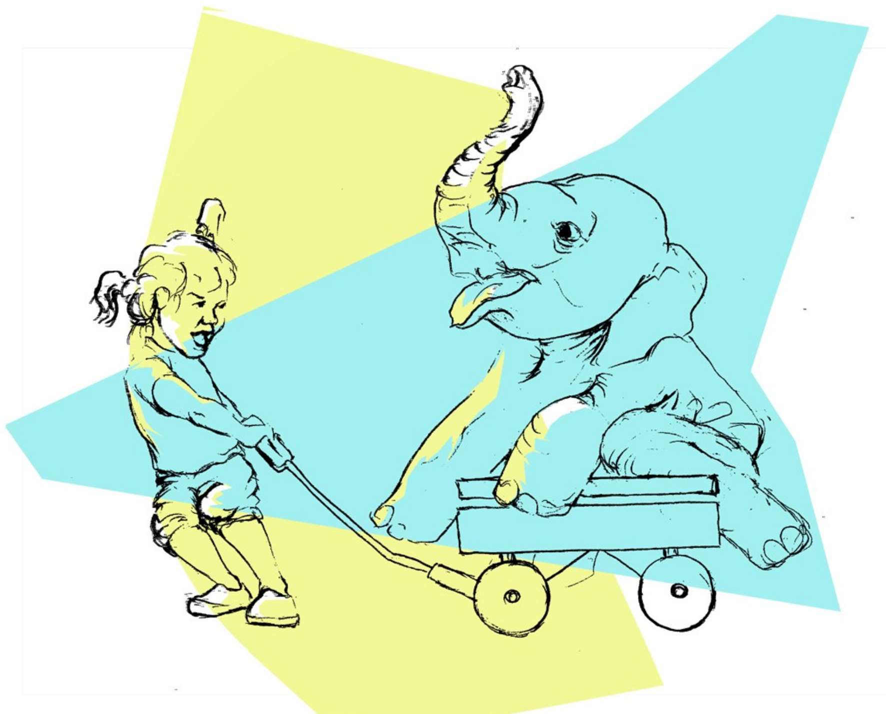
Newton's first law (the law of inertia) somewhat implies mass: An object at rest wishes to stay at rest and a moving object will maintain a constant velocity unless friction or some other outside force changes its velocity. What is actually moving? What is changing velocity?

Newton felt that one way to describe mass would be to say that it is the amount of force needed to change its velocity. He noticed quite simply that the more mass something has the more force it takes to move it. i.e. his second law (in laymen's terms): The amount of force needed to move an object is equal to the object's mass times its change in velocity or it's acceleration, force equals mass times acceleration or $F=ma$.



As this illustration of my kid demonstrates it is quite easy for them to pull their wagon with just a small stuffy in it...

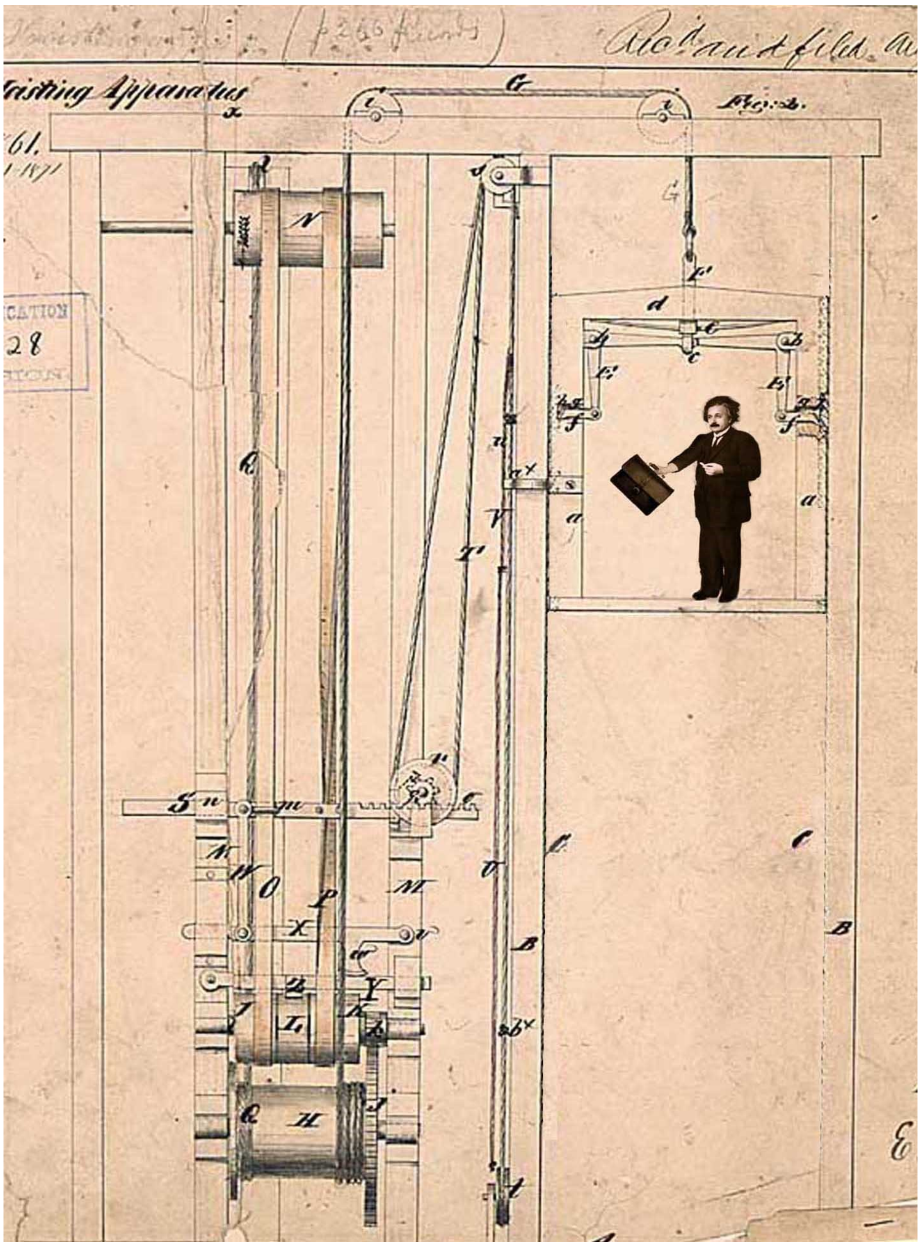
however if the little elephant has the mass of an actual baby elephant of course it becomes very difficult, but the interesting thing is that the force needed for pulling is directly proportional to the mass of whatever is put in their little wagon.



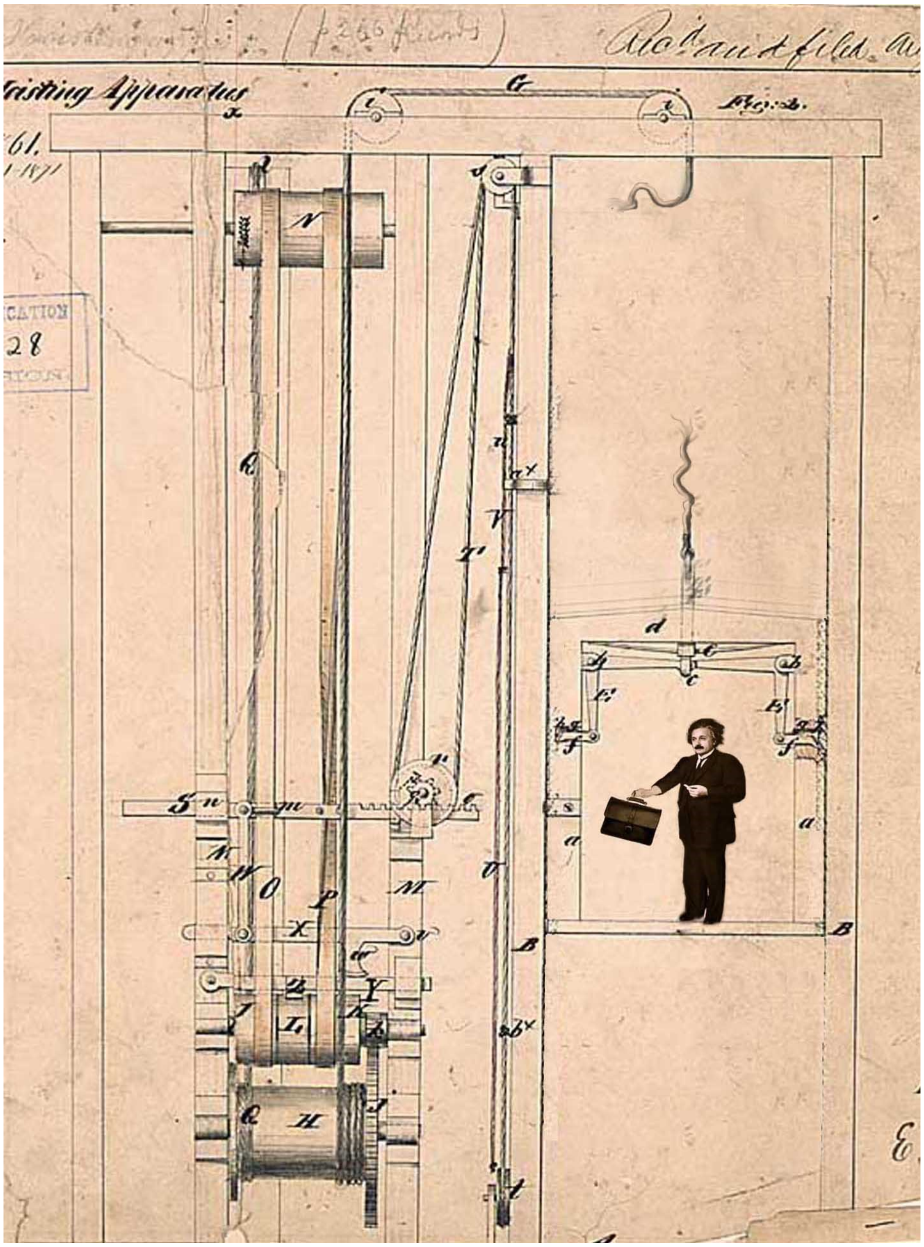
Newton's genius of course is best known for describing the laws of gravity.

He discovered strangely that gravity seemed to be directly correlated to an object's mass, the greater the mass, the more powerful the force of gravity. Upon closer examination it seemed to him that the effects of gravity were the same as those of inertia and acceleration.

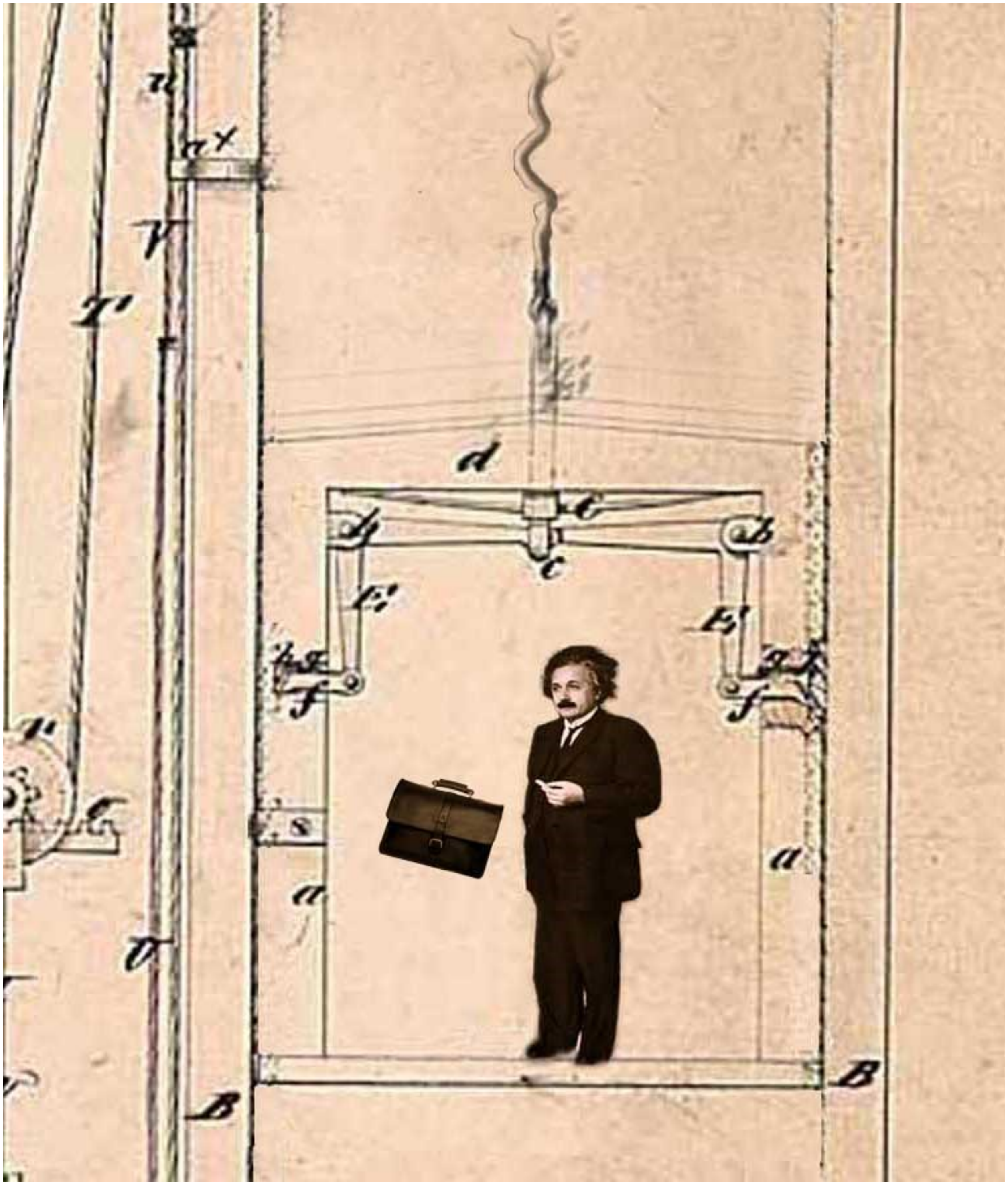
Laurie Anderson put it another way: ". . . You're walking, and you don't always realize it but you're always falling. With each step you fall forward slightly and then catch yourself from falling over and over . . ." Well when I first heard this I just couldn't get over it. I'd get stuck in this loop until my brother who studies physics at Cal Tech explained to me: "Vincent you're not falling down to the earth. The earth is moving up towards you. It's coming up to you at a rate of 32 feet per second^2." The idea that the earth is accelerating up towards me sounds absurd. I am not qualified to explain nor do I fully understand general relativity, however I believe it is helpful to use Einstein's initial thought experiment:



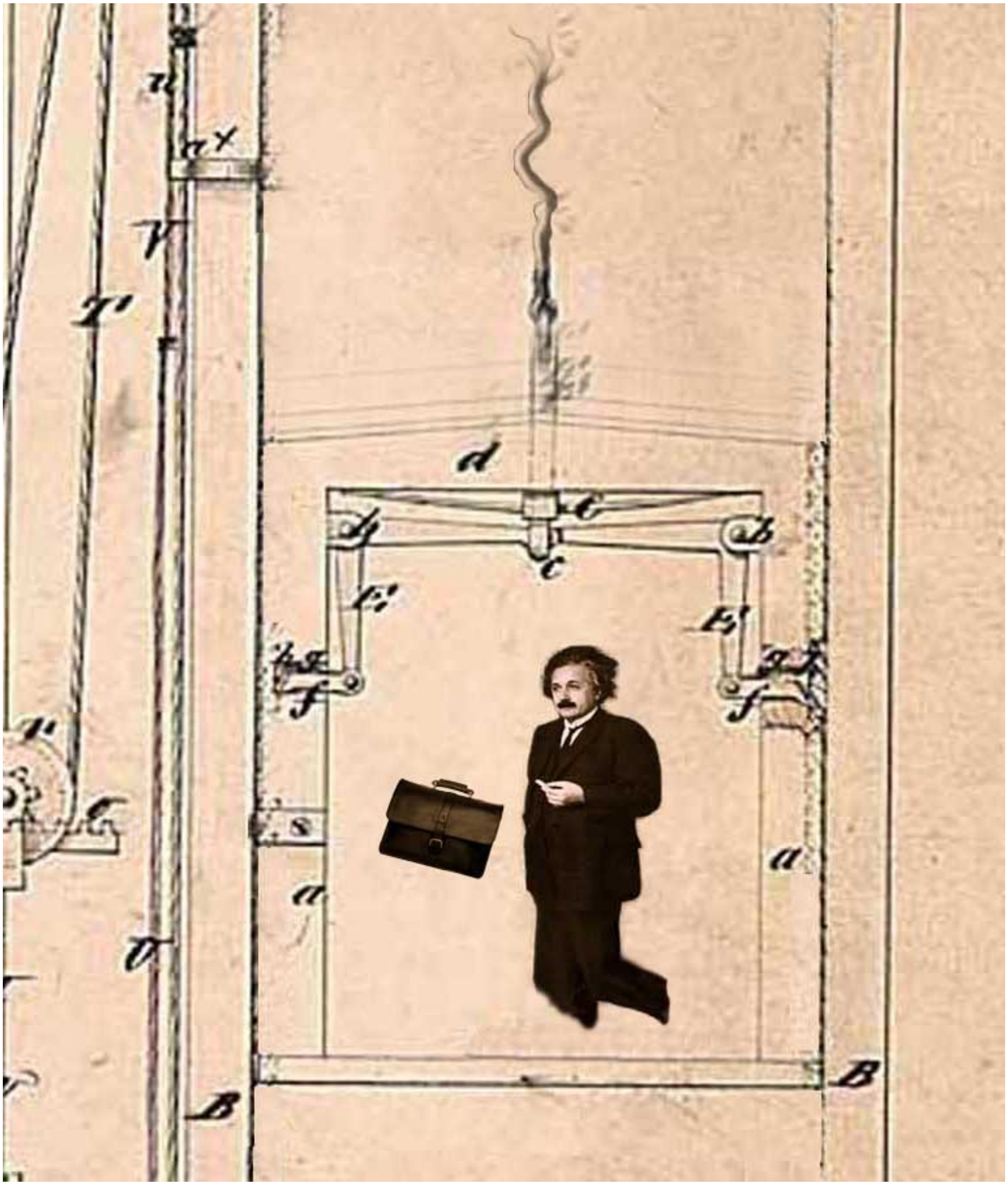
Einstein imagined himself in a mile high elevator.



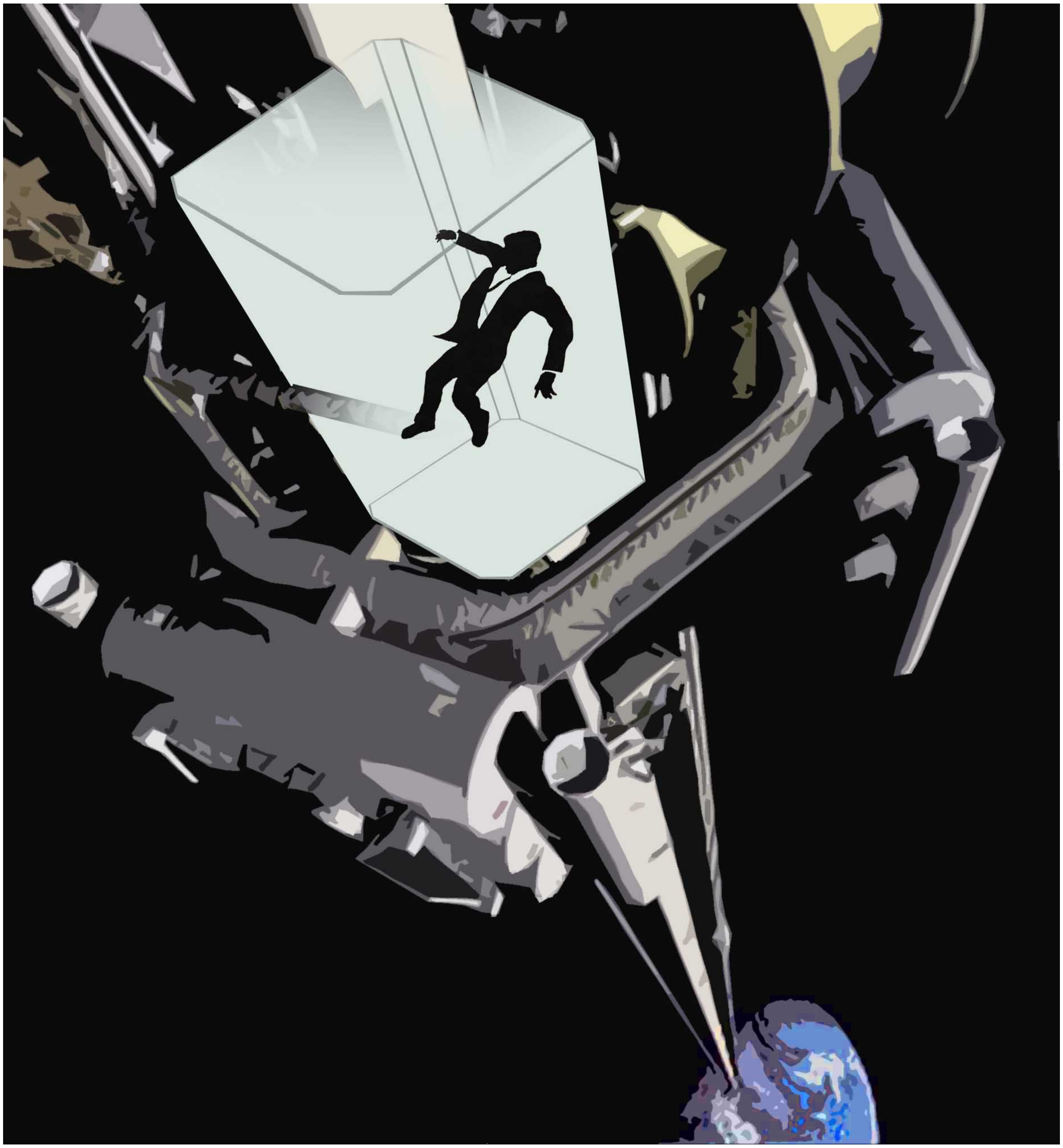
The cable breaks and the elevator goes into free-fall.



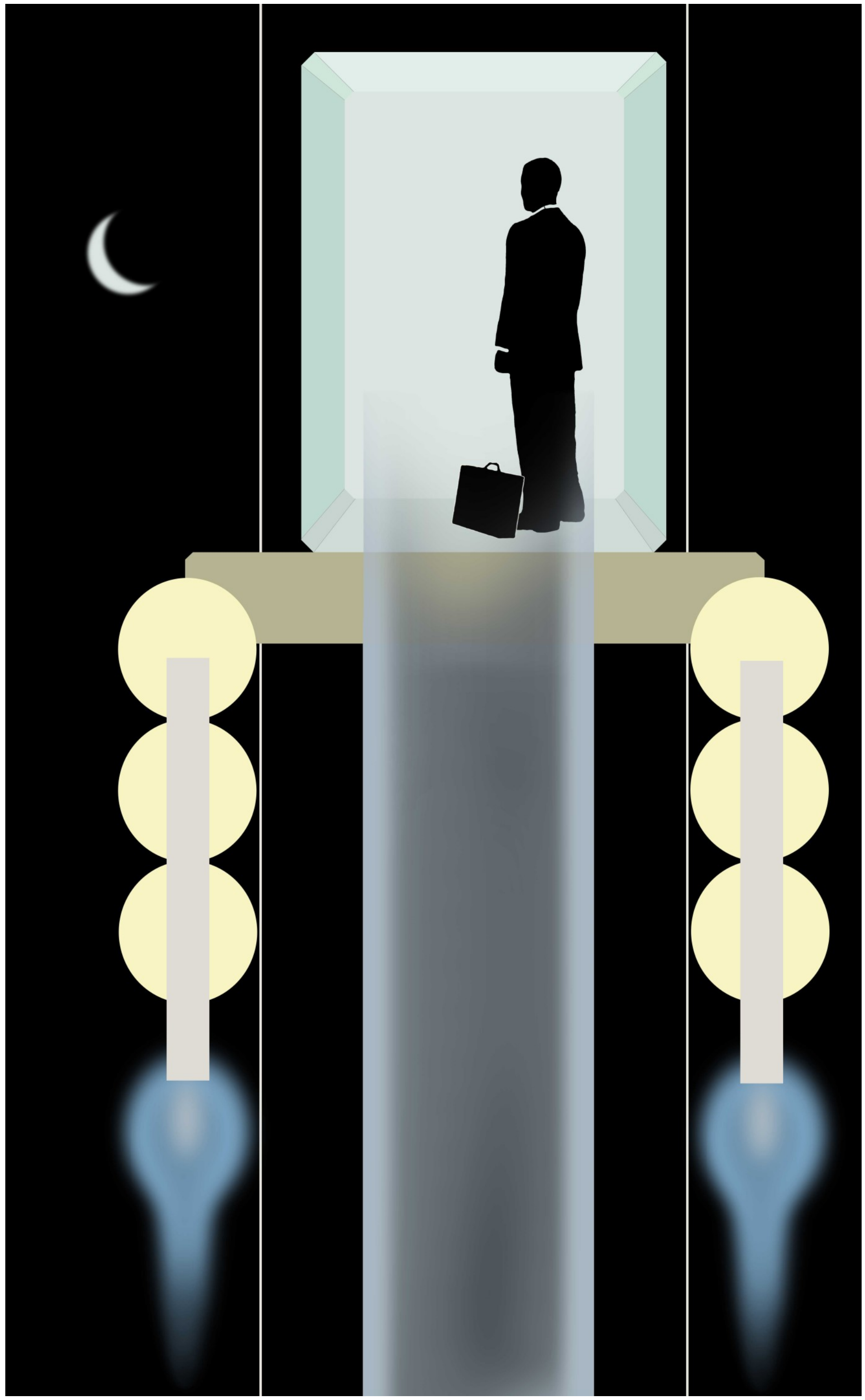
He then imagined what would happen if he let go of his briefcase. In his inertial frame it would appear to be floating in space.



In fact he would seem to be floating. Free falling in this elevator he would feel no gravity. He would seem to be weightless.

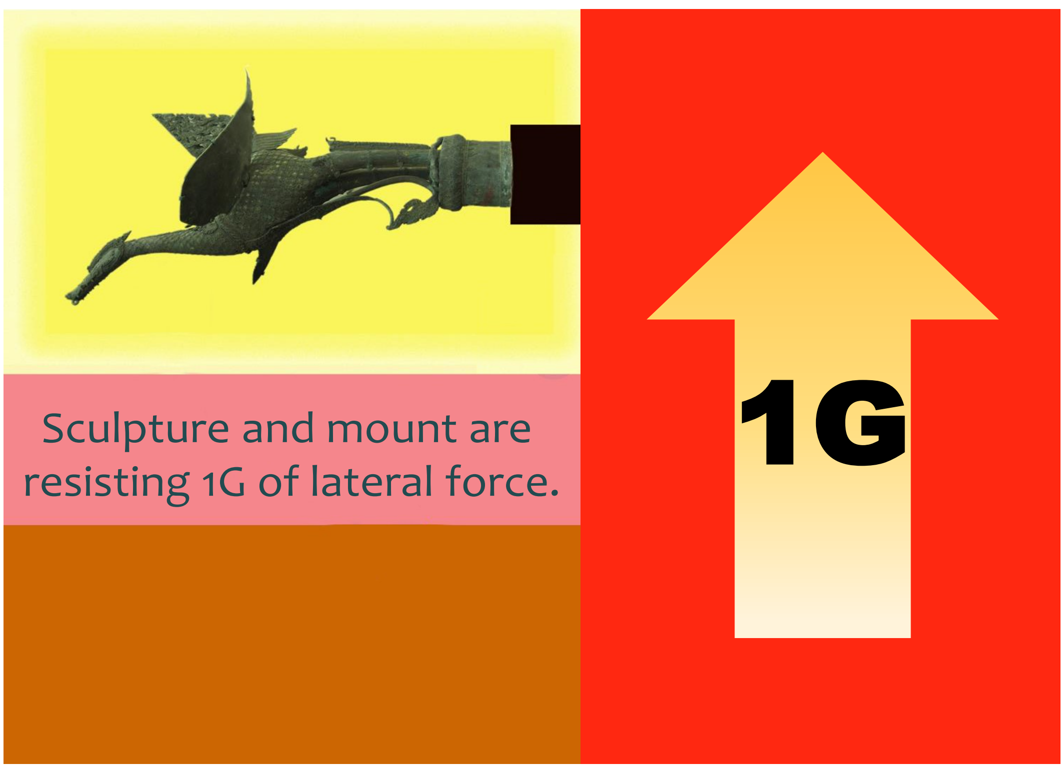


Conversely he imagined taking an elevator into the weightlessness of space.



And then imagined accelerating at 32 feet per second squared. Einstein would appear to be experiencing earth's gravity. The fact is that, from the reference point of an inertial frame, (that is from an observers specific point of view) gravity and inertia are the same.

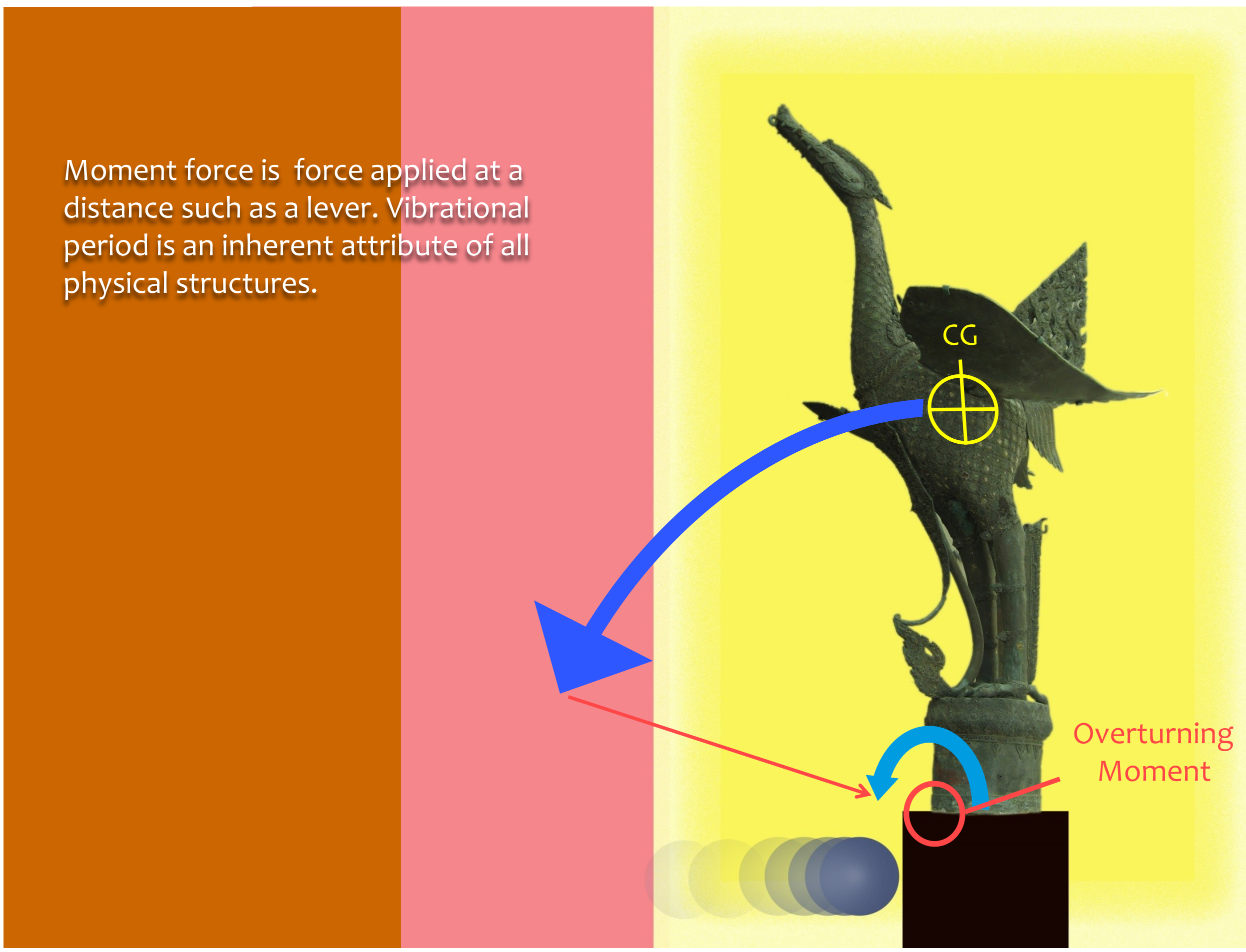
If we imagine this Guanyin sculpture in the weightlessness of space we can rocket it at a certain acceleration that for all evidence, intents and purposes would feel exactly like earth's gravity. That arbitrary number is 32 feet per second squared, what we call one earth's gravity or as they say one "G". We use this as a constant only because we are all familiar with it; we just need to do a couple of pushups to know exactly how powerful a force that is.



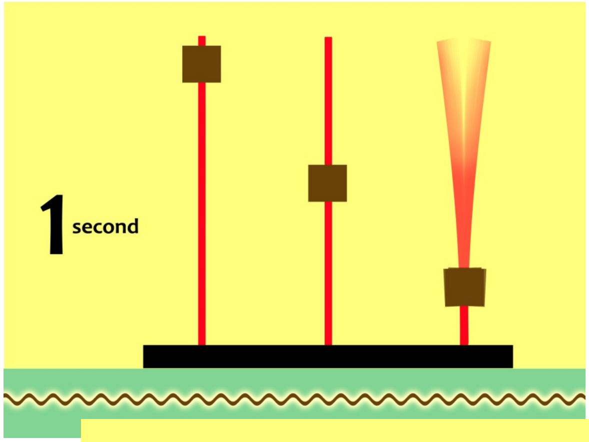
Now in the event of a ground vibration the object must overcome lateral forces virtually the same as the vertical. As seen here an object feeling a lateral movement of one G (which is very powerful for a quake) is actually the same as if it were somehow mounted perpendicular to the wall.

The problem is that we have to take both the vertical and horizontal forces into account, that is the seismic vibration and the vertical gravitational force. This means we must look at the vibrational period (of the object and the possible quake) combined with the rotation about the overturning moment or more simply the combination of the sideways movement of the object and its tendency to fall over.

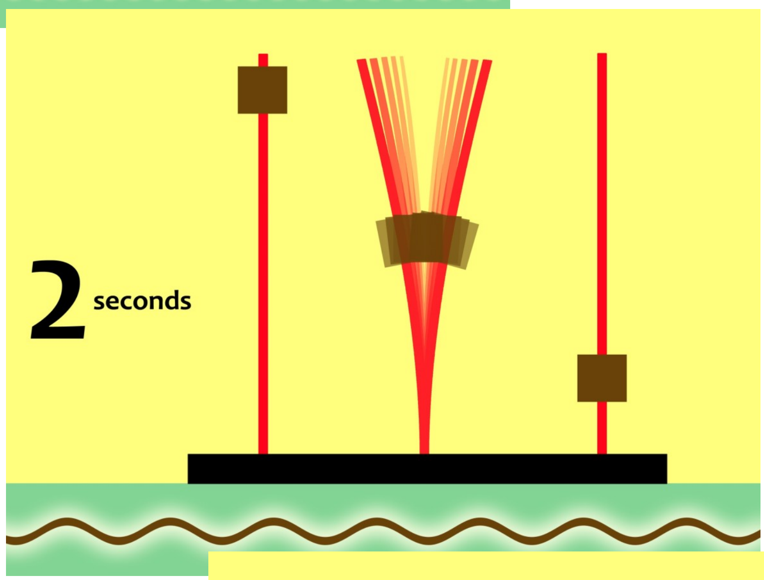
Moment force is force applied at a distance such as a lever. In this diagram force is applied from the objects center of gravity to the axis point where it will be rotating from and perhaps overturn. It might also be noted that this is reversed if we change the inertial frame as we did in the study of gravity.



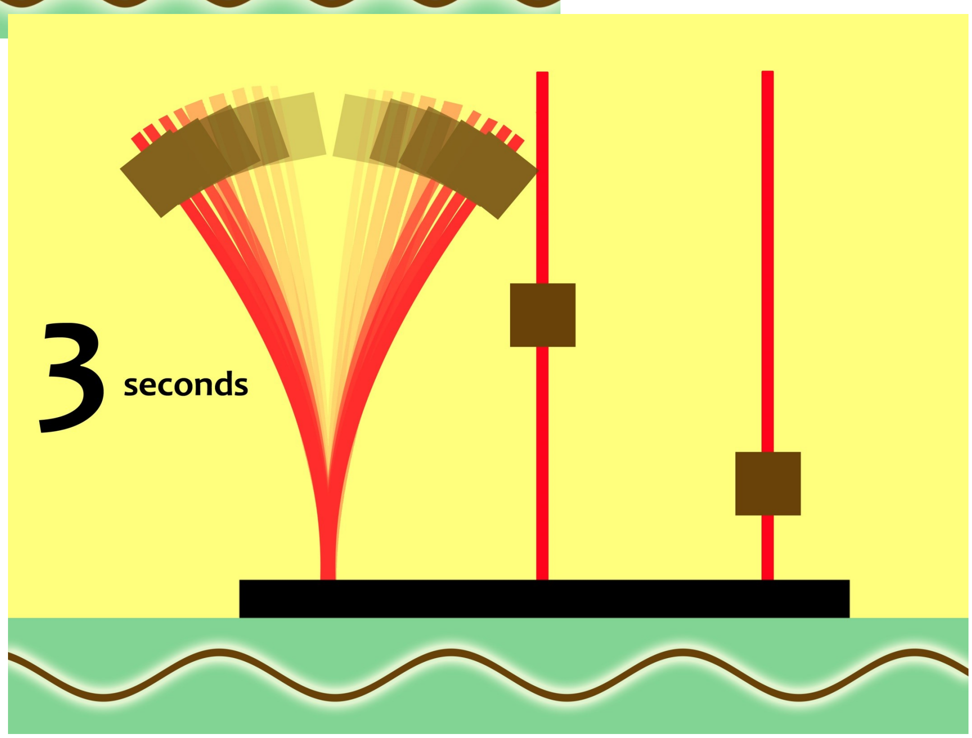
This force as we said is measured by mass (calculated by weight) and acceleration. Many buildings have vibrational frequencies that can be felt, usually driven by their HVAC or other mechanical equipment. Our old building had just such a vibration which had very little effect on the art work.



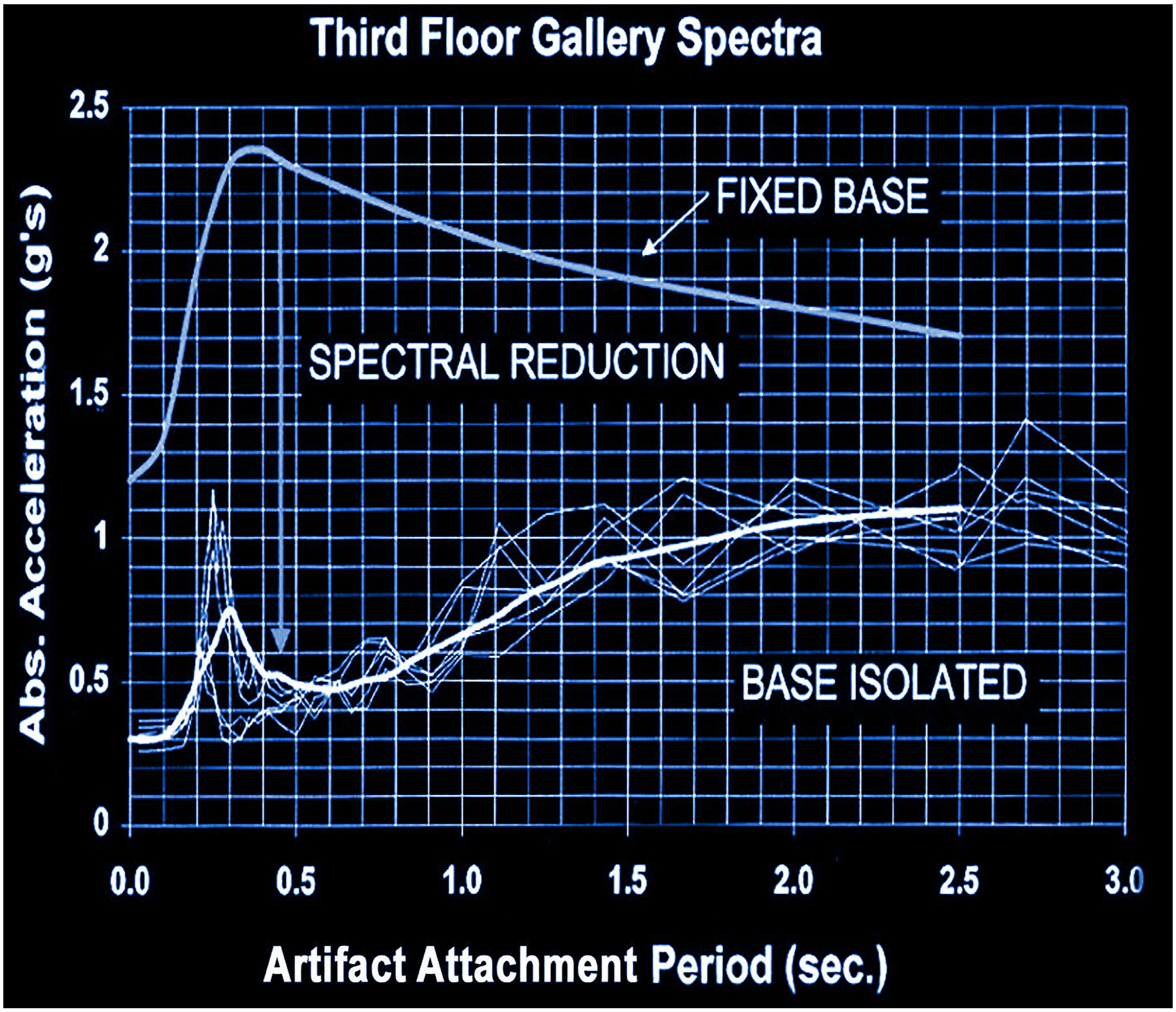
Vibrational period is an inherent attribute of all physical structures. Most structures have an inherent frequency they wish to vibrate at much the way a tuning fork oscillates at a particular frequency to give us a clear single note.



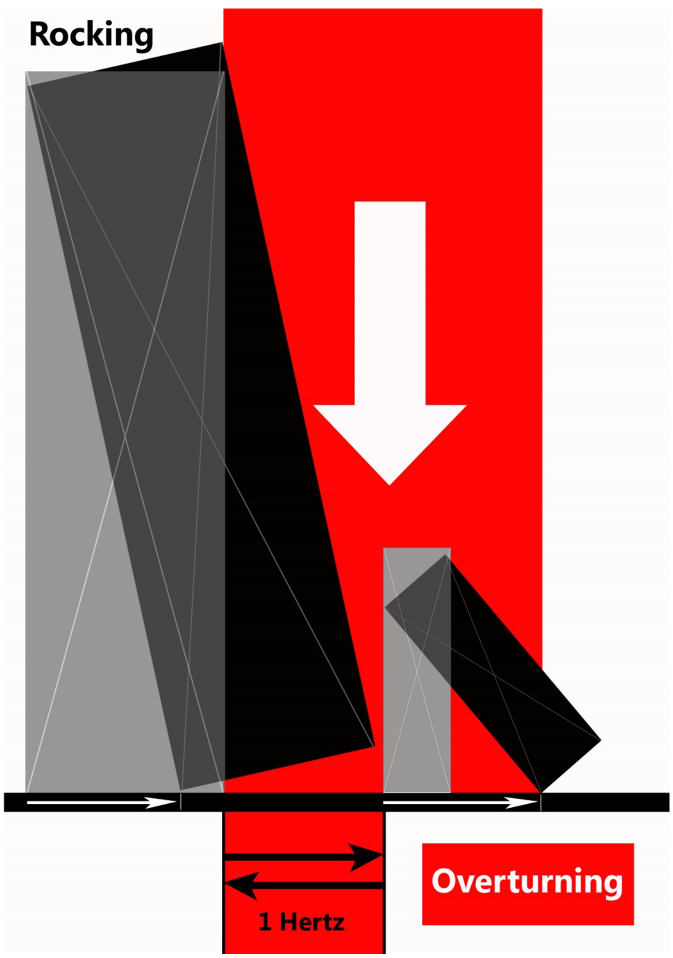
The fork oscillates at a specific number of times in a specific time period. If an earthquake vibrates an object or a building at its inherent vibration the results can be catastrophic.



This graph illustrates the effects of input seismic accelerations to the inherent vibrational periods of structures in our building (pedestals/art at the Asian Art Museum). It was used to compare a stiffly reinforced museum building to one tuned with base isolators. The top line is the stiff structure and the bottom is the base isolated. A fascinating note on this graph is that acceleration initially increases with inherent period then drops. After the initial drop there is a slow climb in the base isolated structure. It doesn't meet the top line but the increase is still significant.



The severity of earthquakes varies greatly. If you look on the USGS earthquake map every day you will see a slew of small earthquakes rattling away on the many faults throughout the U.S. These are measured on the moment magnitude scale. The moment magnitude scale (which has replaced the Richter scale) takes into account all mechanical displacements in all dimensions of time and space: duration, length of rupture, size of dip, transform and oblique displacements etc. These smaller quakes may be low on the moment magnitude scale but can be very powerful since there are many other factors: time duration, frequency, acceleration to name a few, all of which are quite variable. We don't notice them mostly because they are so short and vibrate at frequencies in the area of the many ambient vibrations we experience daily. Additionally many buildings such as skyscrapers have a sway usually generated by wind. This "sway" is really just a vibration with a very long period. Again most objects will not be in resonance with this "sway" and will suffer no damage.



Some earthquakes will damage only smaller objects. Vases and knick knacks may overturn and fall off shelves while larger statues will remain unscathed. It is often believed that it's because the larger objects are heavier and stronger that they are undamaged but in actuality it has more to do with geometry and nothing to do with an object's mass. The exception occurs when rocking is amplified usually due to a resonance effect which can be quite common in quakes of greater duration.

This diagram illustrates how the vibrational period of the ground motion has a large enough displacement to overturn the small object where a larger object with the same aspect ratio will only rock.

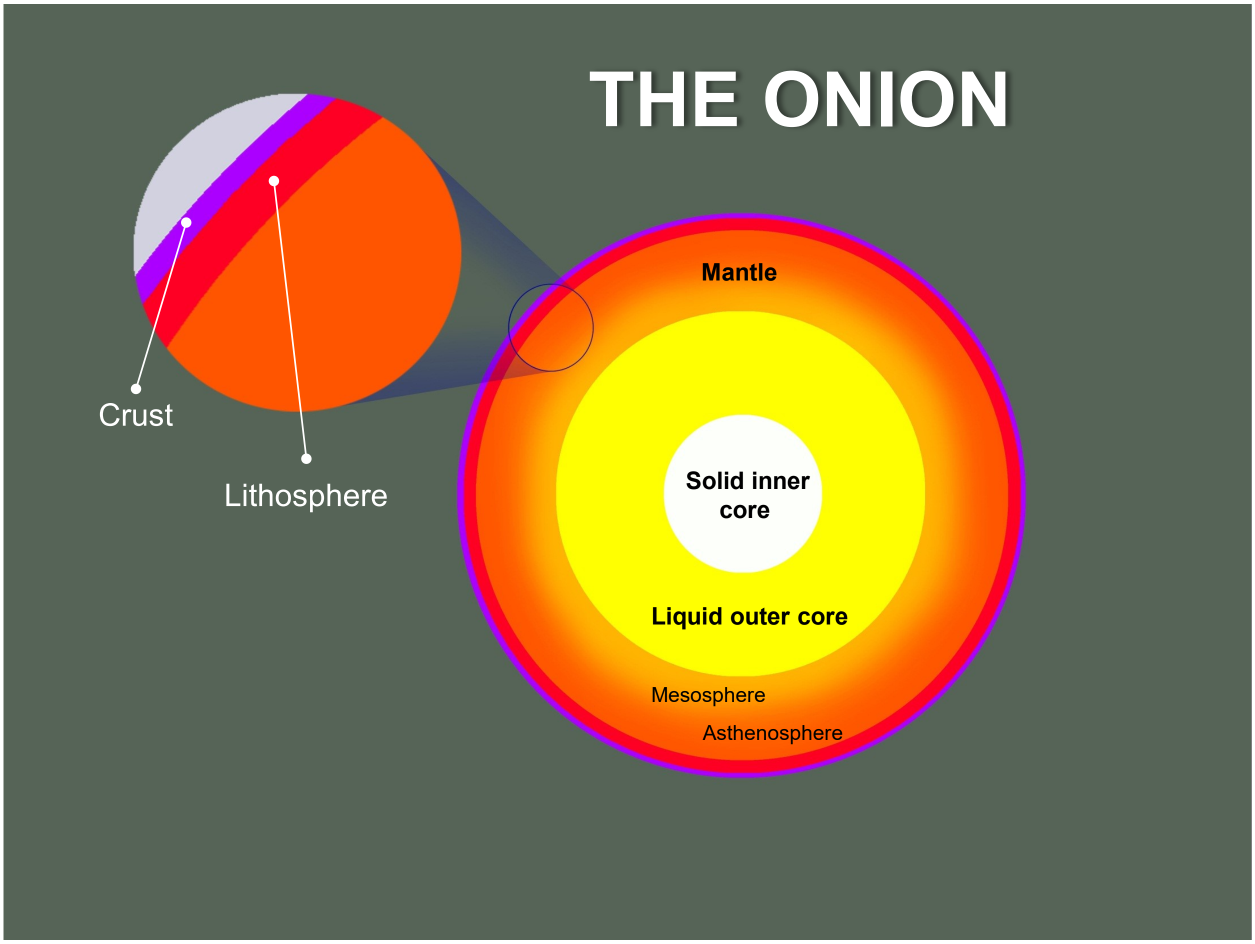
Near epicenter events can also be explosive enough to create high vertical accelerations that will aid the eventual overturning. In California this vertical peak dissipates quickly with distance from the epicenter. In most earthquakes the ground may shift an inch or less. Larger rarer earthquakes (or near fault scenarios) will of course not only have greater accelerations and velocities but larger ground displacements. High velocity (over .7G let's say) long displacements (over about a foot) are rare. Displacements like this would generally have a speed more akin to the skyscraper sway. Still a large object (like a tall pillar unmoored or tall statue) may find itself in dangerous resonance with just such a sway.

When an earthquake vibrates a building at its inherent vibration the results can be quite devastating. A great example of this is the performance of buildings during the great Mexico City earthquake. In certain areas of the city all buildings that were between 6 and 15 stories were leveled... they just shook themselves apart, while buildings that were smaller and buildings that were taller while not remaining unscathed did not suffer a complete collapse. Less dramatically when our own building was modeled and tested by the engineering firm Forell/Elsesser it was discovered that the greatest motions were not in the top floor as one would expect, but on the floor below.

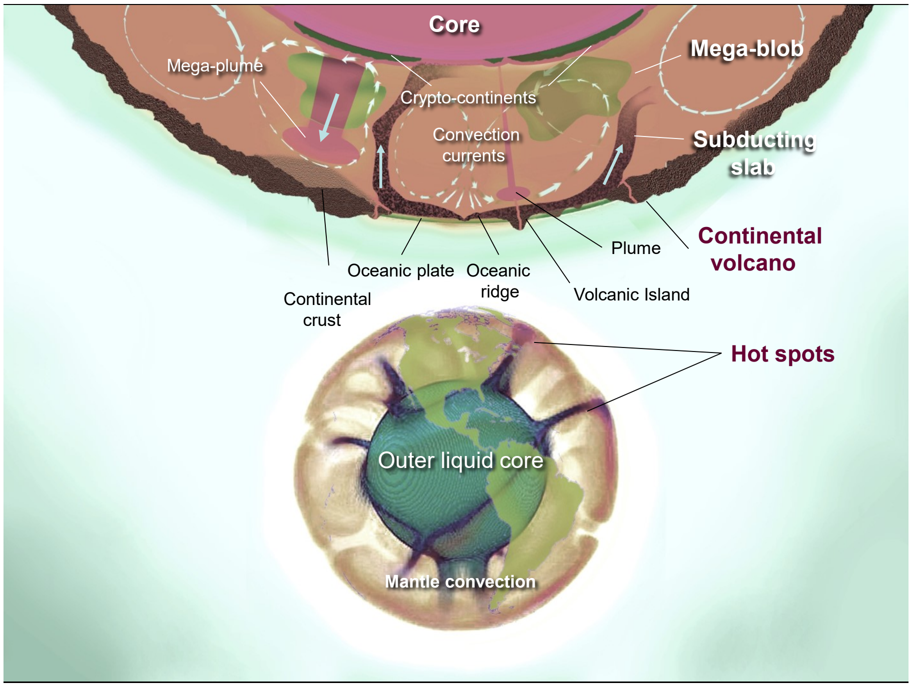
Let's now go back in time before the earth even existed. Gravitational forces brought elements of a gas nebula, dust, asteroid and comet like material together to form some sort of a proto earth: an agglomerating hadean cacophony of birth and destruction.

It is believed that the proto planet was so liquid and violent that words like earthquake and volcano are essentially rendered meaningless. There were constant bombardments of large bodies that kept the earth liquid molten and spinning at an ever faster rate. This molten state lasted long enough for heavier elements such as Iron (and to a lesser extent platinum and iridium) to sink to the core.

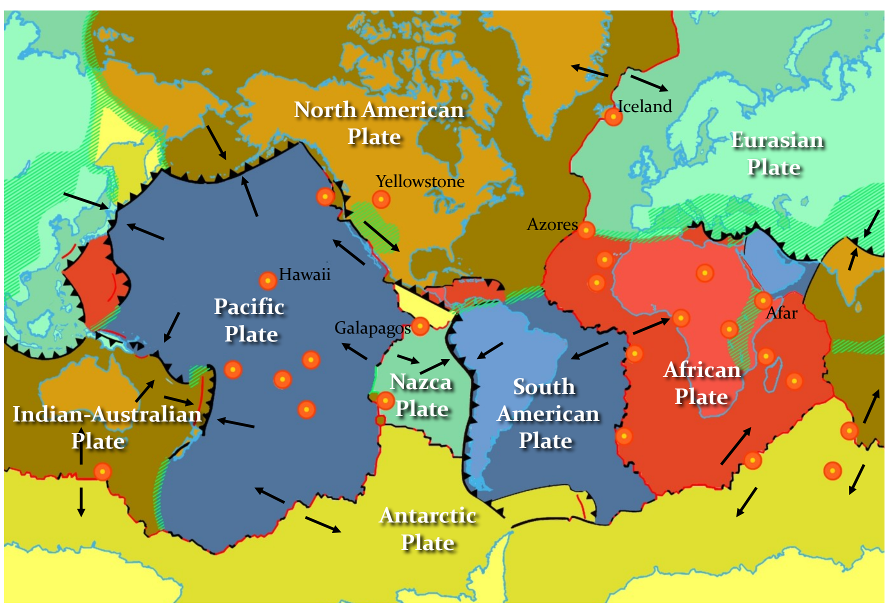
As the earth and its orbital neighborhood reached equilibrium the planet began to cool, the rocky crust formed and the mantle congealed into an elastic structure.



Today through the analysis of seismic waves pulsing through the earth we are able to extrapolate structures deep within it. We have an inner core of solid iron, an outer liquid core still churning from rotational forces and kept heated by the decay of radioactive elements. Crypto-continents float on this infernal sea. In the mantle, semi molten convection currents and plumes of liquid magma are glacially churning moon sized mountains under our feet.



These engines are generating the march of the tectonic plates we see on the surface.



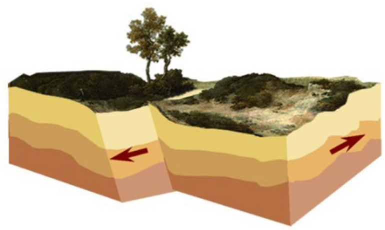
These movements (that sometimes prove catastrophic) manifest themselves in the form of earthquakes.

For our purposes we shall say that an earthquake is a sudden rupture in the earth's crust usually along fault lines.

Types of faults are categorized by their slip and mechanical forces:

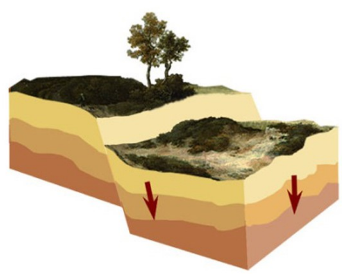
A strike-slip fault or transform fault is caused by the movement of rock horizontal to the fault boundary. Such movement is found along the San Andreas system for instance.

Transform Fault



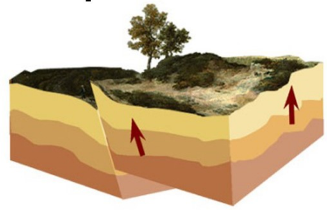
There are two kinds of dip-slip faults. The first is called a normal or extensional fault. This is described as an extension of the ground plane perpendicular to the fault line causing the ground on one side to drop.

Extensional Fault



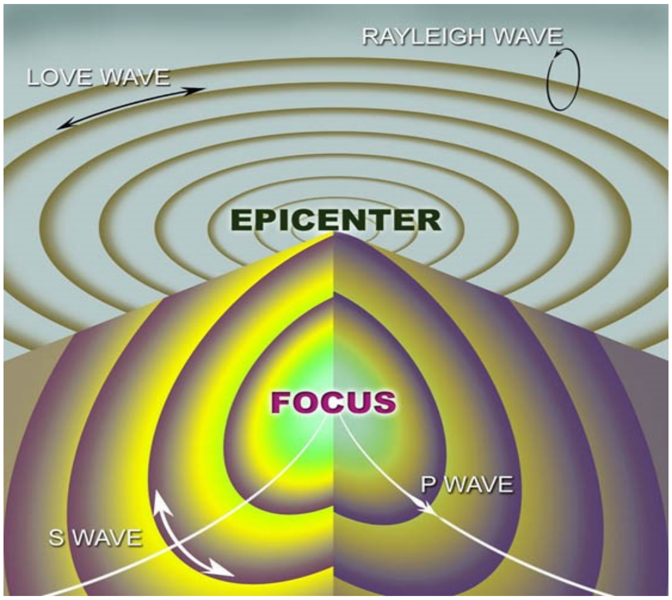
The second and rarer type of dip slip is called a thrust or compressional fault which occurs when there are compression forces of the two rock slabs perpendicular to the fault line causing an upward thrust of one of the fault planes. The Northridge Ca. quake as an example ruptured on a hidden or blind thrust fault.

Compressional Fault



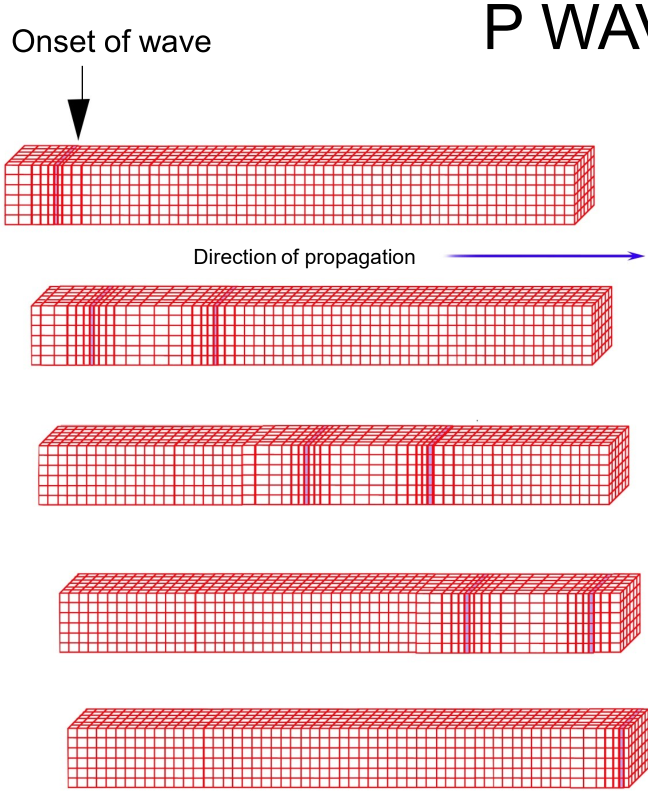
An oblique-slip fault is a combination of strike-slip and dip-slip mechanics.

Earthquakes propagate their forces via seismic waves. These waves are divided into two main categories: body waves and surface waves. Body waves emanate directly from the source of the quake deep within the earth, while surface waves radiate out from the epicenter which is the point over the source or focus.

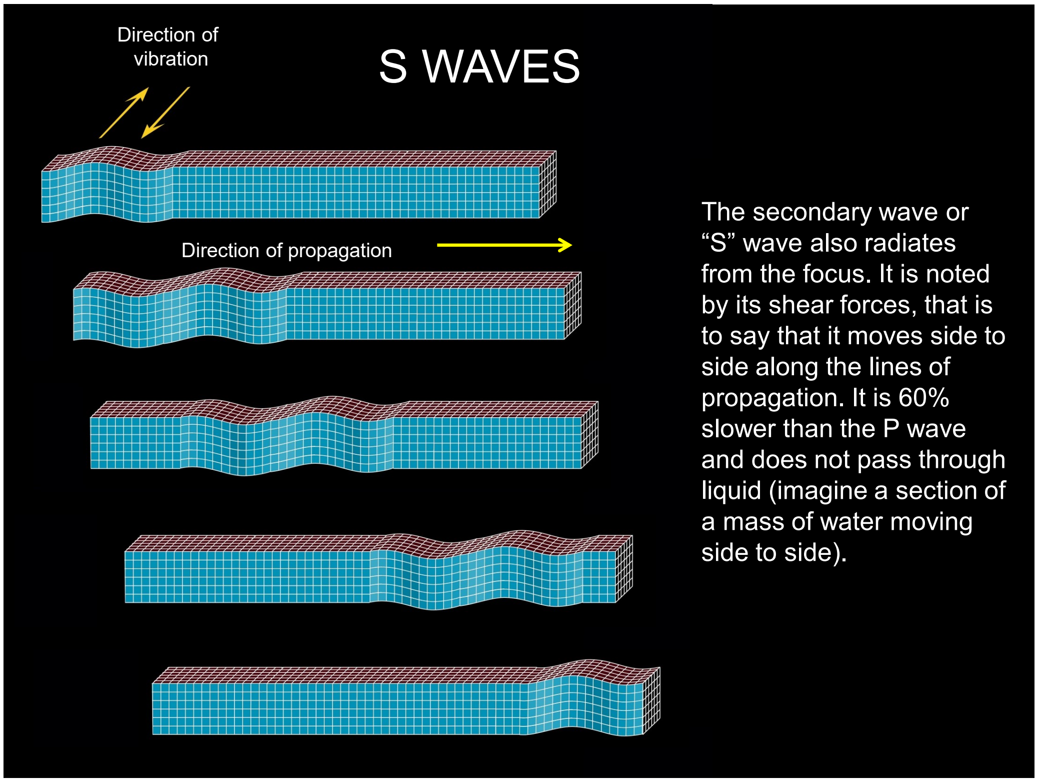


There are two kinds of body waves:

P WAVES

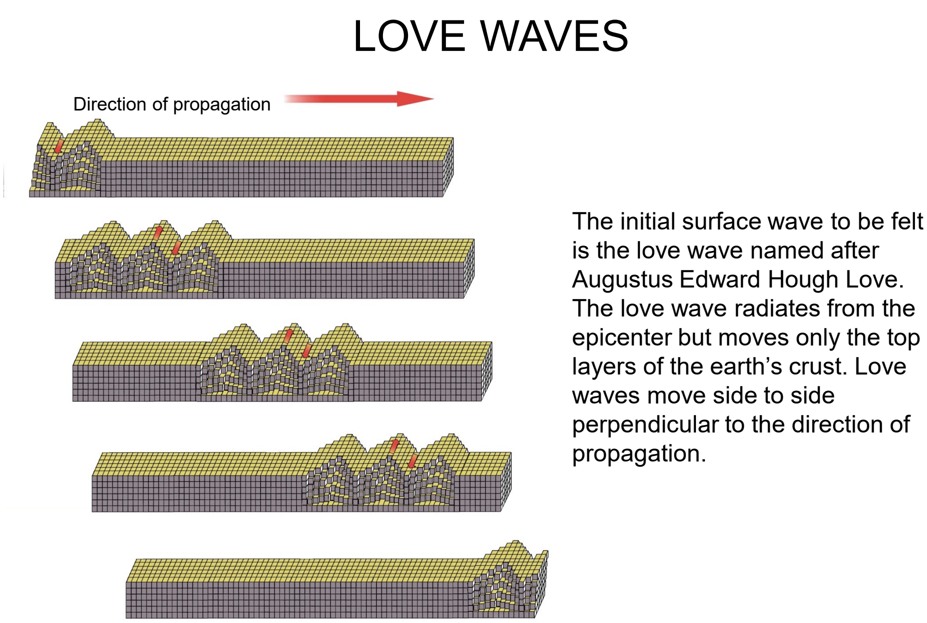


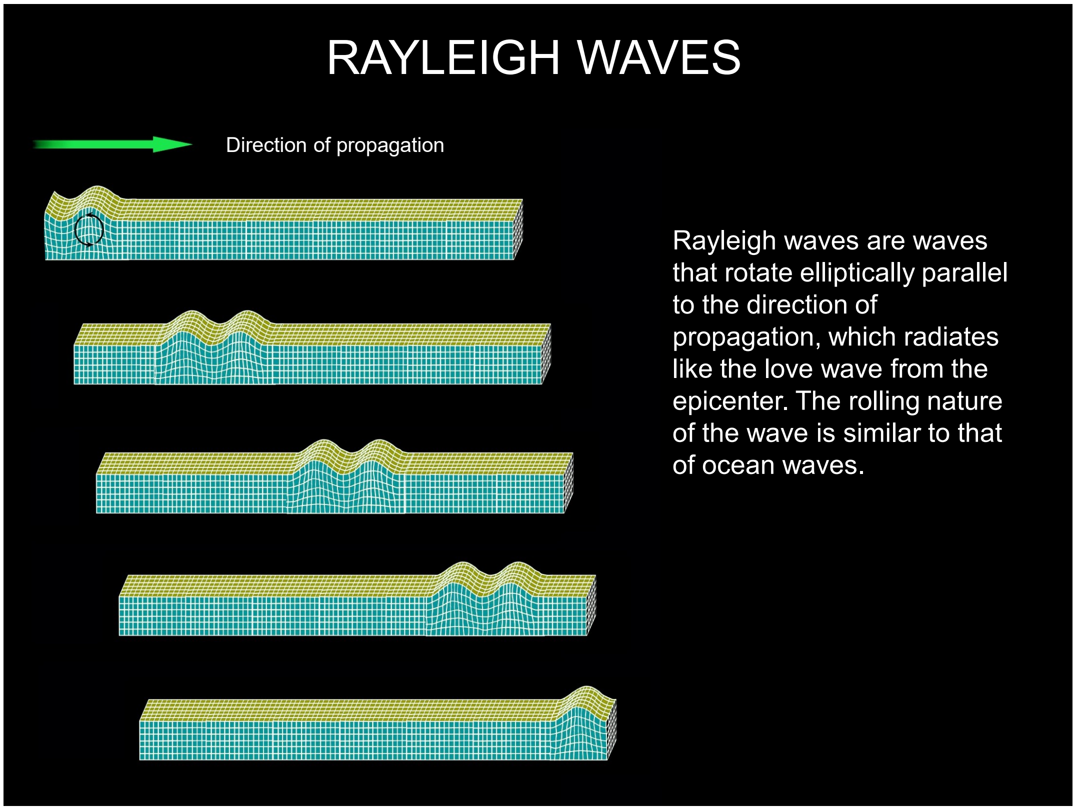
The primary wave or "P" wave radiates from the focus. This wave is the fastest and highest frequency of all the waves. It is related to and moves near the speed of sound with a similar compressive wave pattern through the medium, that is alternately compressed and dilated along the lines of propagation.



Because the waves propagate within the earth and because of their different behaviors we can measure with contemporary instrumentation and computer modeling the structure of the earth's interior.

Additionally there are two types of surface waves:





Surface waves occur from the combining of s and p waves. They are slower than s and p waves but because of their larger particle motions they account for a great deal more of the destruction.

The Northridge earth quake as an example was explosive at its epicenter with vertical accelerations beyond 1G, however the greatest recorded accelerations were 7k away at the foot of the mountains in Tarzana. It has been suggested that surface waves moved south through the valley and “crashed” like ocean waves against the mountains. Further study has led to greater understanding of what is called the “Basin Ridge Effect”. Evidently it is not only surface waves pulsing against the sides of the L.A. basin but the joining of body waves and surface waves coming together at these locations.

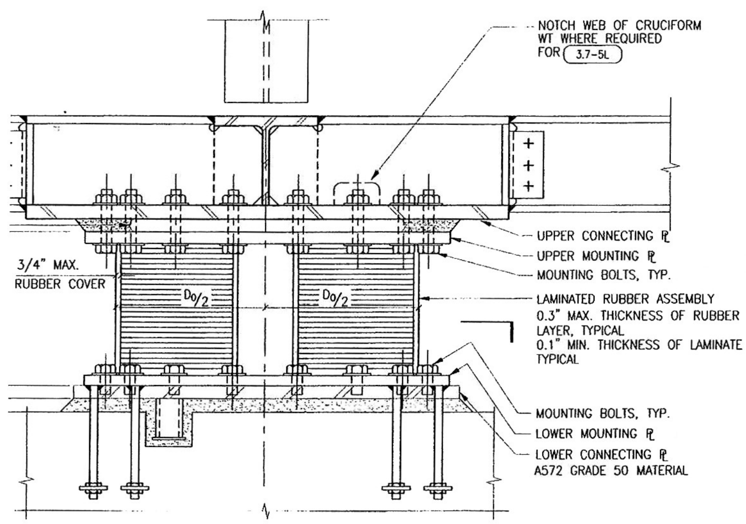
This brings me to what we might call the first point of disaster mitigation: location. Basically this means designing around the probabilities of a disaster in the location where the objects are being displayed. Los Angeles is probably one of the most difficult places to make these predictions since the faults in the LA basin are so web like and ubiquitous (never mind the fact that every new earthquake tends to produce the discovery of a new fault).

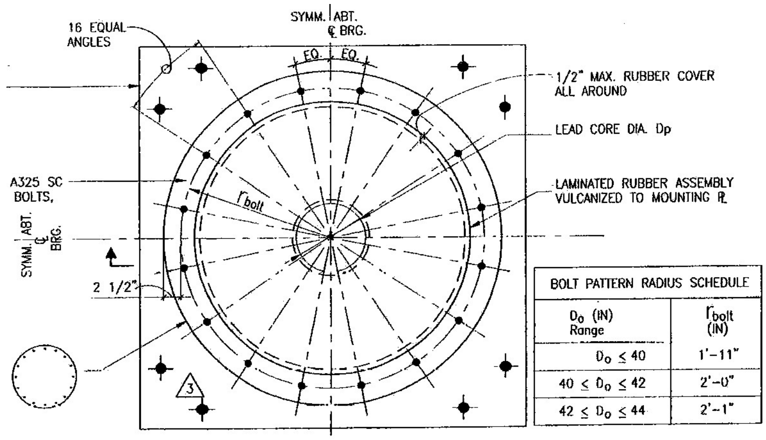
The Northridge quake is a great illustration of near epicenter phenomena and the incidence of destructive Raleigh waves. Bedrock is considered fairly stable as compared to alluvial valley soils and clays. The geology of southern California is a great mix of these structures. Of course being on bedrock is most advantageous and in the valley waves propagate more easily. On the boundary between the two is where one may experience the most violent shaking.

To the north in the San Francisco bay area the faults are much better defined.

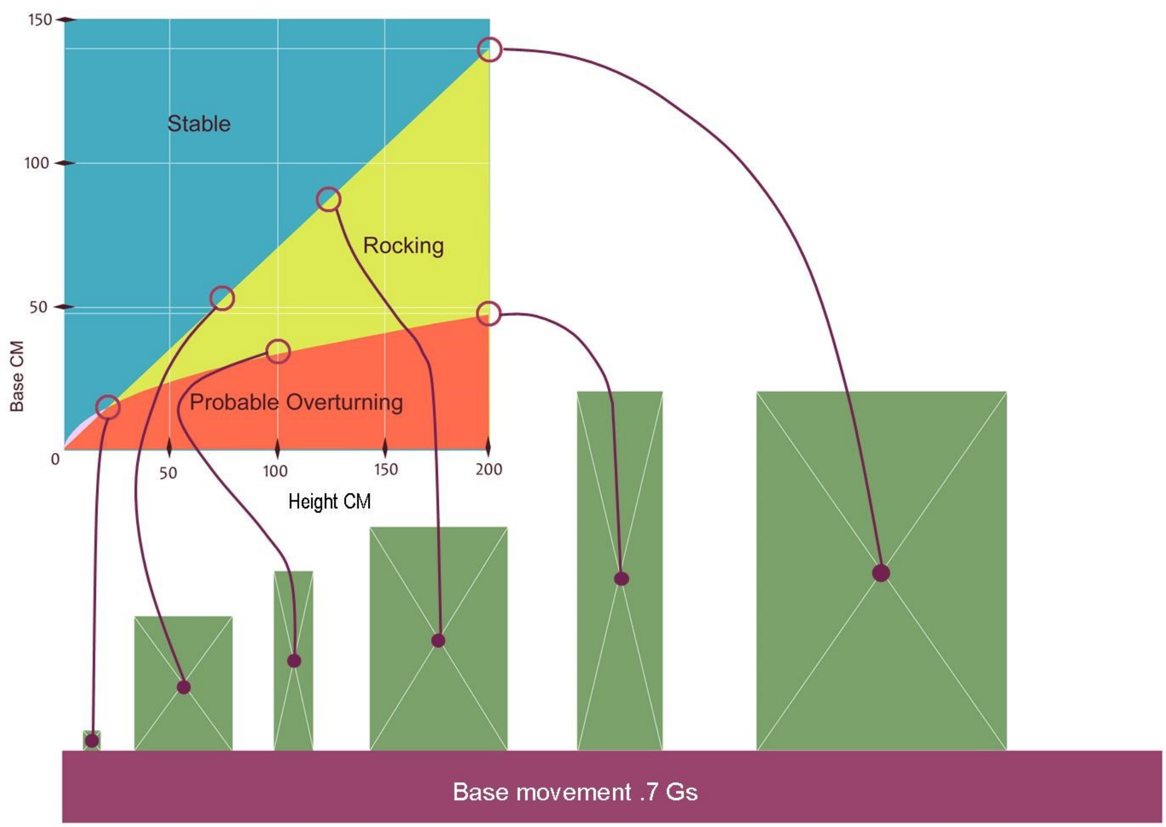
Although the San Francisco Bay Area has a much less complicated geography than the L.A. basin and vicinity it is home to the largest transform fault in the state: The San Andreas Fault, which runs the length of California and delineates the boundary of the North American and Pacific plates. The fault cuts just offshore of the city about 8 miles from downtown where the Asian Art Museum resides. Although we are fairly assured we won't be experiencing near fault phenomena we are close enough to receive accelerations over 1G in the event of a great quake such as the 1906. Though our building rests on fairly stable soil many parts of the city are on landfill. In a seismic event many of these soils will go into "liquefaction" causing them to literally jiggle about similar to a turbulent ocean. This phenomenon caused the complete collapse of many structures in the bay area during the Loma Prieta earthquake including the deadly collapse of the I-80 Freeway in Oakland.

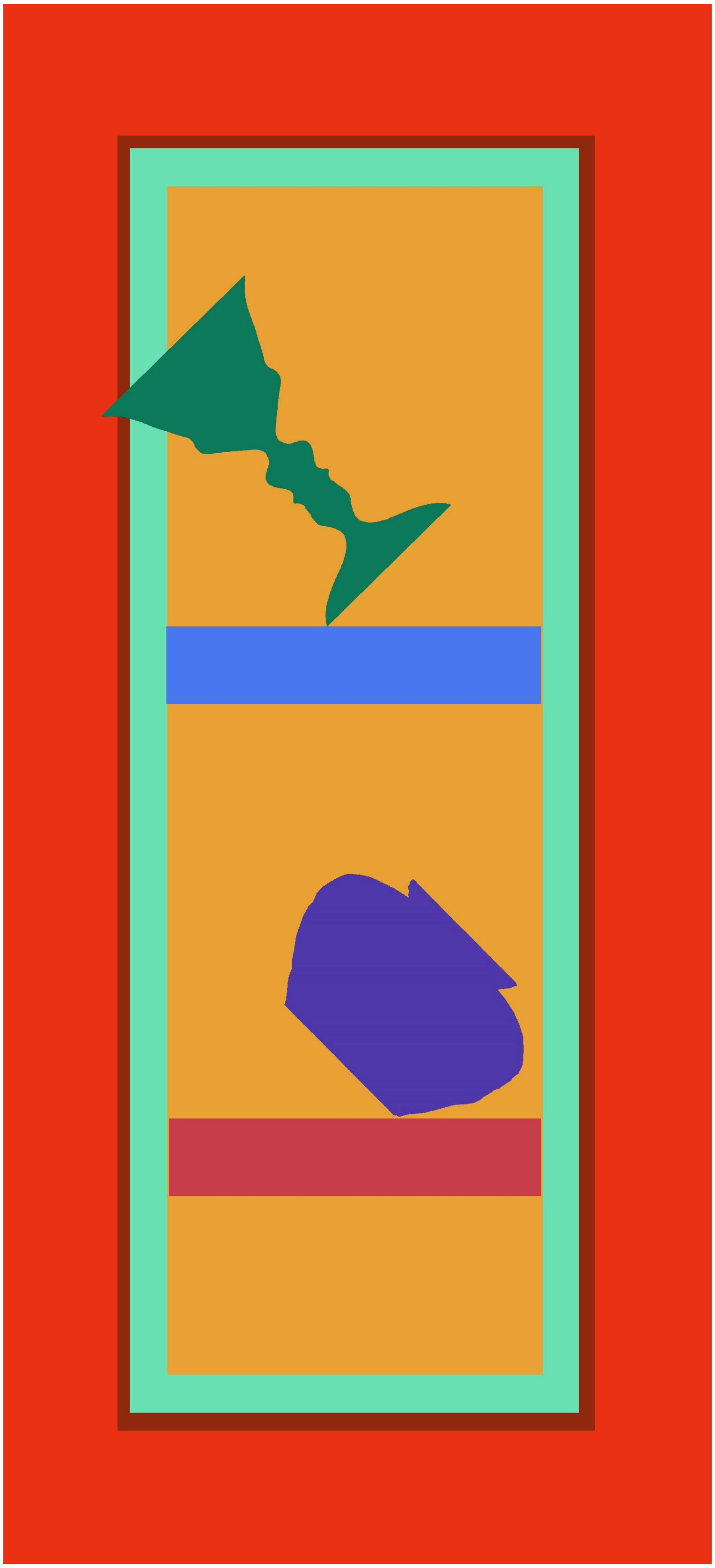
In determining the probabilities of hazardous motion for our objects of course it is important to consider the building itself. Our building was retrofitted in 2003 with base isolators so that we would be able to decouple ourselves from the most severe ground motions. The base isolators are able to take the most severe ground motions of over 1.5gs to just .3 on the 3rd floor where the greatest displacements and velocities would occur. This does not mean that we do not have to make mounts. It only means that we can make mounts strong enough at our own facility. These are still significant accelerations and the methodology depends on anchoring all pedestals and objects stiffly as even small vibrations can do damage especially if the objects are in resonance.





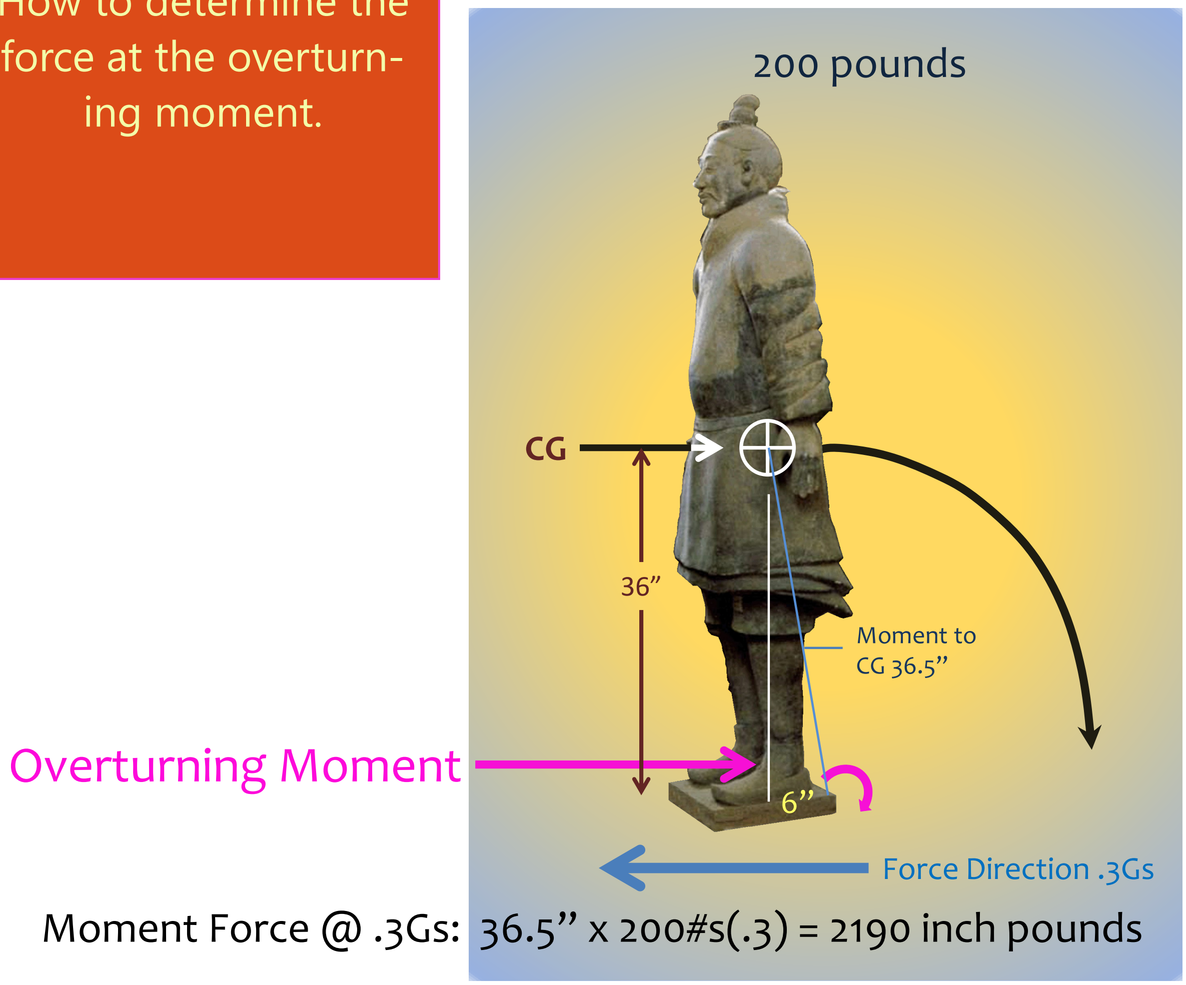
Bob Nigbor did a thorough study for us in 1992 of object protection measures and their effectiveness. He came up with this rocking and overturning chart as a basic means of analyzing possible dangers. I added models of the aspect ratios noted on the chart so you could easily get a visual sense of the shape of stable and unstable objects. This chart reflects a one dimensional view of a .7G acceleration to the pedestal under an object. It does not account for resonance effects or the effects of higher accelerations which may occur in other buildings or display scenarios.





We actually have access to a natural measure of acceleration: Our own earth's gravity. We can hold an object and tilt it on edge to get a sense of the forces of acceleration that may occur; for instance at 90 degrees a mount would have to hold an object undergoing an acceleration of 32 feet per second squared or 1G. If a mount can withstand this kind of force it has the capability of mitigating a powerful seismic event. Because of resistance and torsional effects this does not give us an accurate number at other angles for instance a 45 degree tilt does not give us exactly .5 Gs of acceleration. It will give us a general sense of stability however and a means of intuiting measures that may need to be taken. As an example the purple jar on the bottom may just need some weight inside it to give it a stable mass. However the cup on the top will undoubtedly need an armature to keep it from overturning.

How to determine the force at the overturning moment.



A good way of calculating forces that an object and its mount may encounter is of course to use Newton’s second Law. First we will need to determine an objects center of gravity. We will use this terracotta warrior as an example. I modeled it to find its center. Next we need to find its axis upon which it may overturn. We will call this the overturning moment. Moment force can be described as force exerted at a distance such as the force exerted by a lever. We will need the weight of the object and the expected acceleration. Again: Newton’s Second Law is:

Force = Mass x Acceleration

We will say the force here is the mass measured by weight (200 Pounds) times the expected acceleration at our site (.3Gs) or: Force = 200 x .3. This will give us 60 pounds. Whew … not bad you might say. There is still a little something called leverage (also known as rotational force or moment) we still need to take into account. For this we need to multiply our force by the distance from the center of gravity to the overturning moment which is 36.5 inches which will give us a moment force of 2190 inch pounds.

Stable Shape

Wd>Fh

Weight = 200 pounds

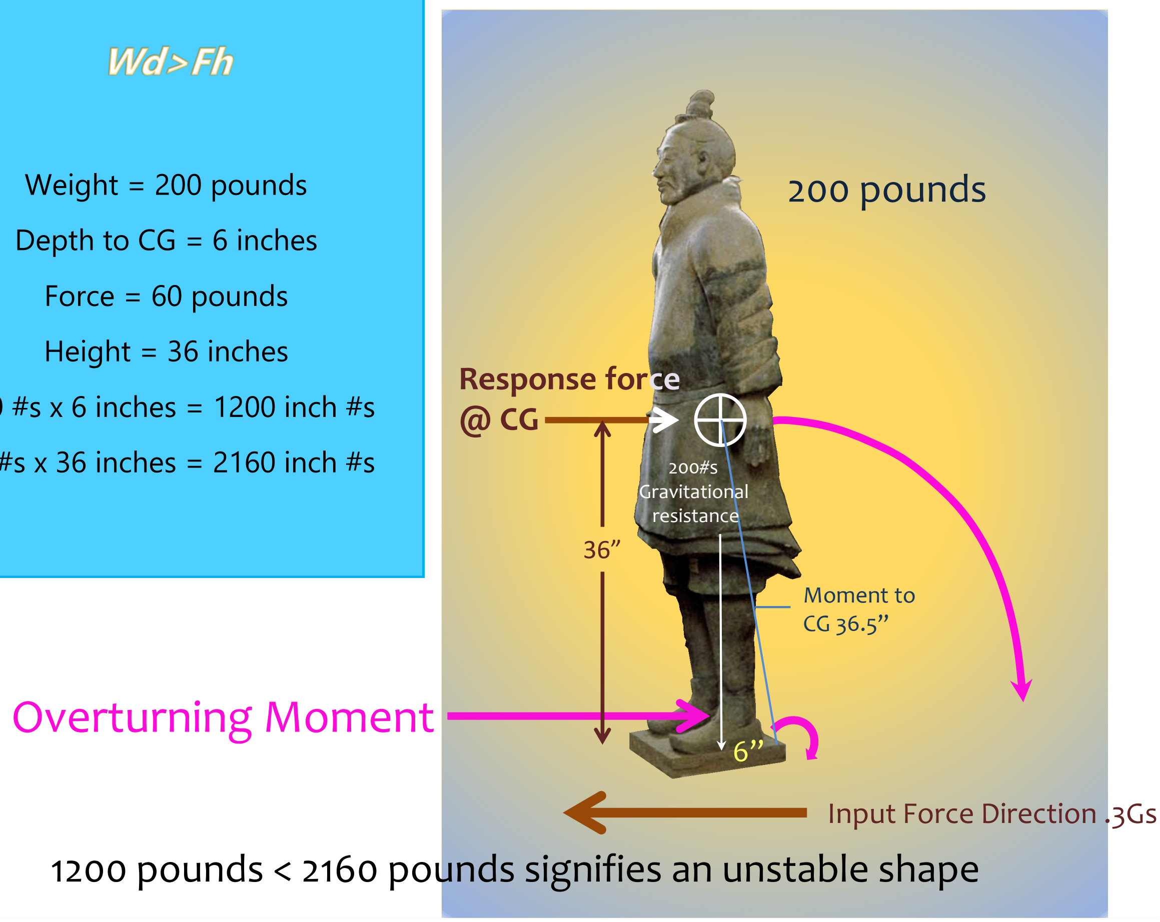
Depth to CG = 6 inches

Force = 60 pounds

Height = 36 inches

200 #s x 6 inches = 1200 inch #s

60 #s x 36 inches = 2160 inch #s

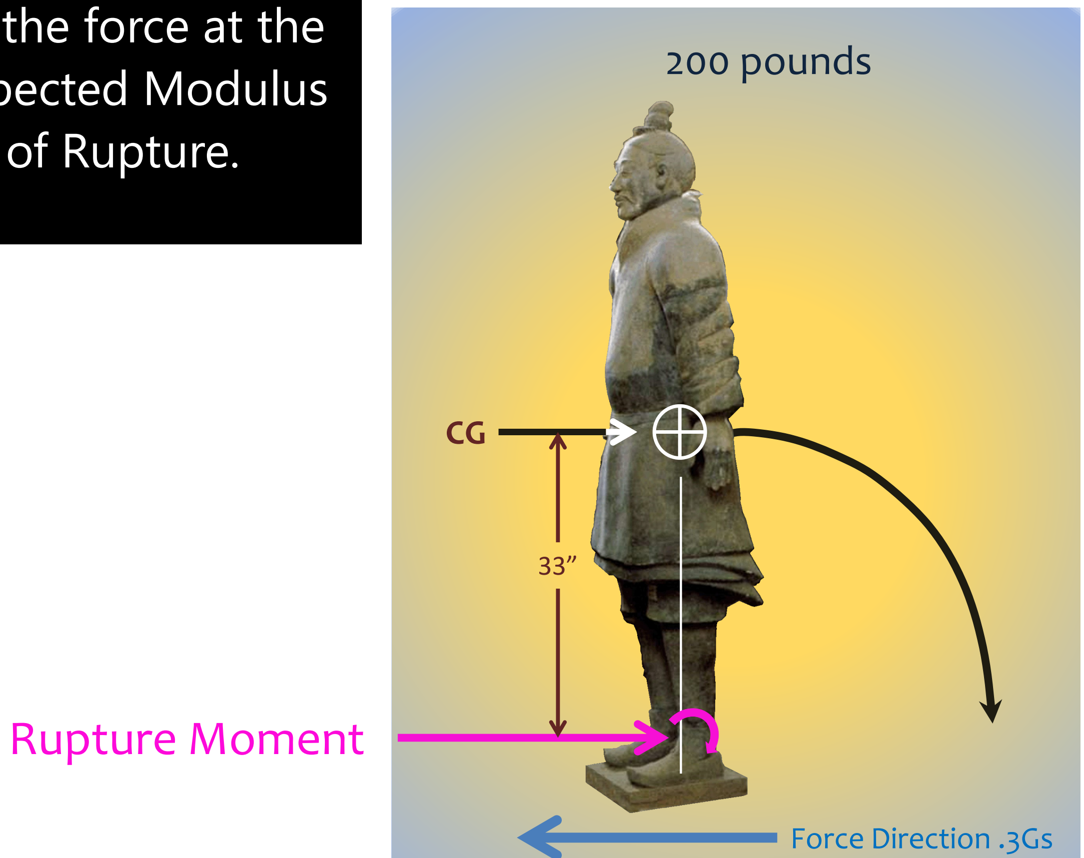


One thing we haven’t touched on yet is the normal vertical gravitational resistance, which brings us to Newton’s famous third law: For every action there is an equal and opposite reaction. Our warrior experiences an input force of .3Gs. This means of course that at the center of gravity there will occur an equal force of .3Gs in the opposite direction. This however will be counteracted by the earth’s actual gravity: at center there will be a resistance in this case of 200 pounds (the weight of the object). An object is said to be stable when the gravitational resistance is greater than the input lateral force such as an earthquake vibration. This can be expressed as follows:

$$Wd > Fh$$

Where W is the mass or weight of the object, d is the distance from the overturning moment to the center at the floor, F is the input force, and h is the height to the center of gravity. In this instance the gravitational resistance is 1200 inch pounds which is not enough to resist the input of 2160 inch pounds.

A quick way to measure the force at the suspected Modulus of Rupture.



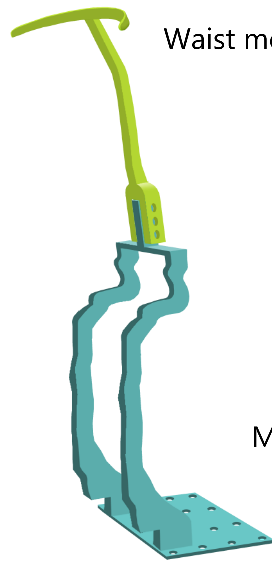
Force Moment of Rupture @ .3Gs: 33” x 200#s(.3G) = 1980 inch pounds

Using Newton’s second law again we can calculate the suspected rupture point of the terracotta if only the base were bracketed. This would be about 33 inches below the center of gravity at the ankles. This result gives us a force of 1980 inch pounds at the ankles. This not only gives us a good idea of the possibility of breakage but also an indication of mount design. As you can see the force gets smaller as we approach the center of gravity allowing us to taper our mount design if we so desire for aesthetic purposes.

In designing mounts for the terra-cotta warriors I needed a broad piece of metal at the base and ankles capable of withstanding over a ton of force. I used ½″ plate steel 4″ wide at the overturning moment. Also they were to be displayed on a very short platform with no access panels for bolting. Because of this I needed a large mounting plate to distribute the load and to give me a large array of lag anchorages to compensate for the lack of machine bolting. Since there was very little time for fabrication once the figures were here I had to rely on adjustable connections for the final fitting.

Back in 1992 Bob Nigbor performed shake table tests using the mounting methods I had appropriated at the time. Because of this test I now use much thicker metal in my mounts and always attach them in at least two places on the art object. This helps the mount and the object to perform as one unit. Form fitting also aids in distributing the forces and aiding in the unifying of the structure as a whole (avoiding dangerous point loading on the object). The object was then cabled with steel rope coated with polyethylene.

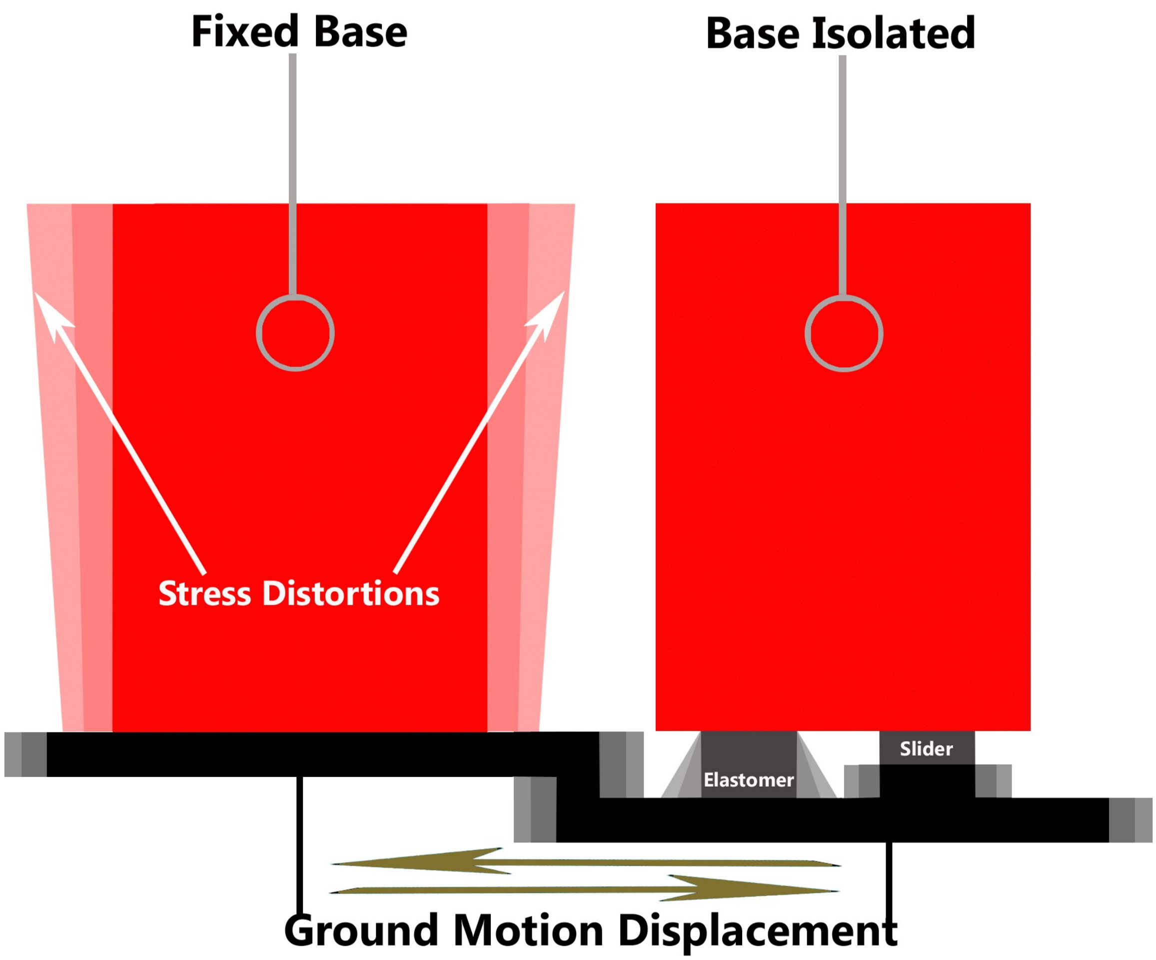
Because of the size and weight of the piece and the fragility of the surface I used ¼″ Volara foam to pad out the mount to the piece.



Our building is sitting on base isolators and because of this we avoid eccentricity in our mounts, that is keeping their mechanics very stiff and simple. By making them as rigid as possible they perform in unison with the building and avoid any resonance effects. The base isolators return the building to center giving it an inherent period (like a tuning fork). Though the movement is broad and slow anything swaying within this period could multiply those forces and create a dangerous situation, hence in general we do not base isolate individual pedestals.

Base isolators work very simply from Newton's first law: An object at rest wishes to stay at rest and a moving object will maintain a constant velocity unless friction or some other outside force changes its velocity.

Simply put the building wishes to stay at rest as the earth tries to force it to move. Base Isolation through many different methods attempts to decouple a structure from those violent forces.



Our building works on giant elastomers, rubber pads with a lead core; simple structures that do several things and are heavily engineered and tuned to the building. These pads relieve some of the accelerations, dampen the extra forces and return the building to center. There are several designs within the building that work in consort together to give a very specific effect.

There are many different types of isolation designs. On the other end of the spectrum there are very simple isolators that merely lower the friction between the ground and the structure. One type we are currently studying is a design by EQX Global. They have come up with plates with variable coefficients of friction (different levels of slipperiness) that can be adjusted to the weight of the object to be base isolated.

The advantage for us is that since there is no return mechanism or inherent damping the object will not find resonance with the building. This is especially advantageous for the use on very large sculpture that would have periods close to our building and have weights beyond what our small shop can handle. The simplicity is also a great factor in that at a relatively low cost it is a very versatile method for mitigating extraordinary forces (the system has been shake table tested at over 3Gs).

This is just a very general scope of the things that need to be considered when making mounts in earthquake country. Geological environments, stable shape, anchoring formulas, and other concepts were all just touched on. I'd like to state here that I am not a scientist or engineer. I am a museum mountmaker charged with mitigating seismic forces on our collection. I have had the great fortune to work with some of the best seismic engineers in the country. Because I am enthused by and have a grasp of these principles as a lay person I can help to pass this information on. My intention is not to demonstrate "the correct way" to do things but to hopefully create a dialogue and even work with other mountmakers, conservators and concerned museum personnel to develope a functional evolving methodology for handling the forces of nature seemingly out of our control.