Reference Frames for Aerospace Engineering

Knowing your reference frames could mean mission success… or failure

Zack Fizell · Following

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Let's say you are an engineer tasked to track the trajectory of a spacecraft on its journey to Mars. You've been studying data on its position and velocity for awhile now. The day has come to finally touchdown, and you are thrilled. But, as you expect the spacecraft to gently approach the surface, it actually SLAMS into the red planet causing you to lose signal. You wonder "how could this happen? The calculations were sound…" It hits you. You used the wrong reference frame in your approach and caused the spacecraft to enter at a higher velocity than expected. A multi-million dollar failure.

Don't be that engineer. Check your frames.

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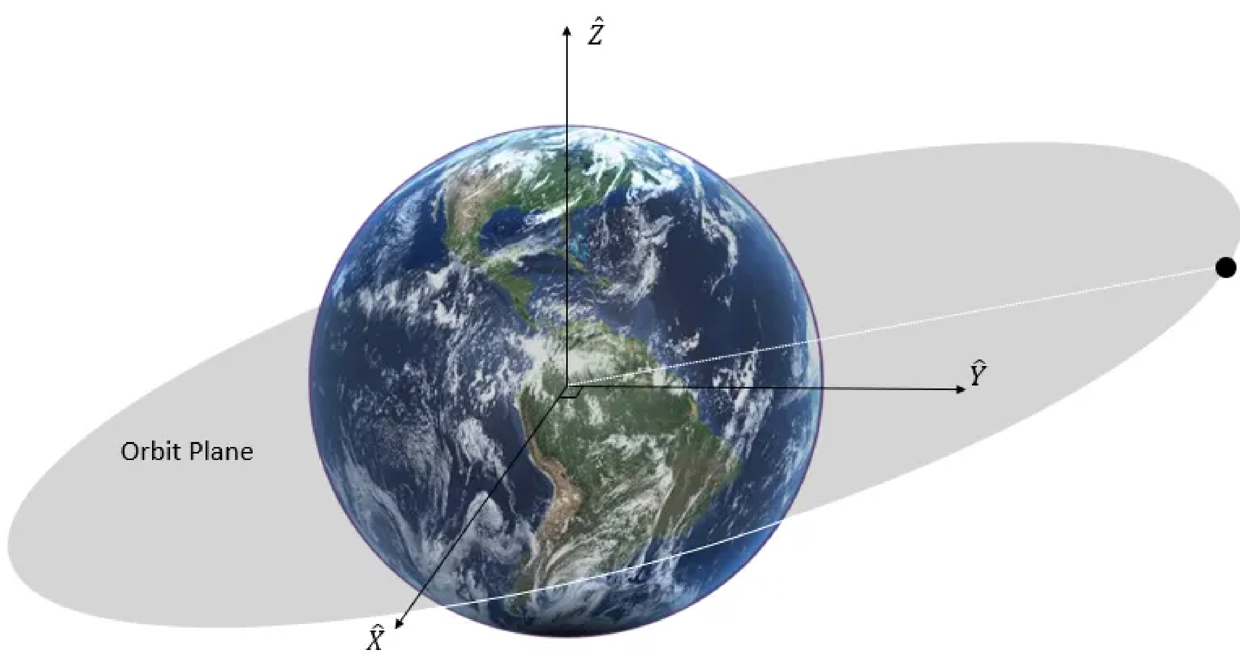
While probably an unrealistic story, it's one that could happen. There have been a handful of occasions where engineers have got it wrong. Just look up the Mars Climate Orbiter mission (those pesky units). Just like mixing up units can cause a $300 million dollar orbiter to crash in to the surface of Mars, an incorrect reference frame can be equally as detrimental to the success of a mission.

This article is meant to help clarify what references frames exist and what their uses might be. To be clear, these are not the only ones. There are many more, but these are the ones I felt were best to write about. Also, note that I used the Earth for these diagrams, but you can easily replace it with another planet, star, asteroid, comet, etc. The concepts remain.

Before jumping into the deep-end, let's cover a couple concepts that will make the following diagrams more intuitive. First, a reference frame, or frame of reference, is a set of three, mutually orthogonal (perpendicular) unit direction vectors. They have an origin, where each of the vector bases meet, and can be time dependent as we will see soon. The importance of reference frames comes in defining an object's position, velocity, and orientation. It's vital for engineers, operators, physicists etc. to know these details. You must know where your object is, how fast it's moving, and how its oriented. Reference frames give you a way of defining these items. I could give you a set of coordinates (X, Y, Z or some other form) without telling you a reference frame, and those coordinates would be useless. It's the reference frame that gives those coordinates meaning.

Without further ado, let's get into a few of the main reference frames for spacecraft:

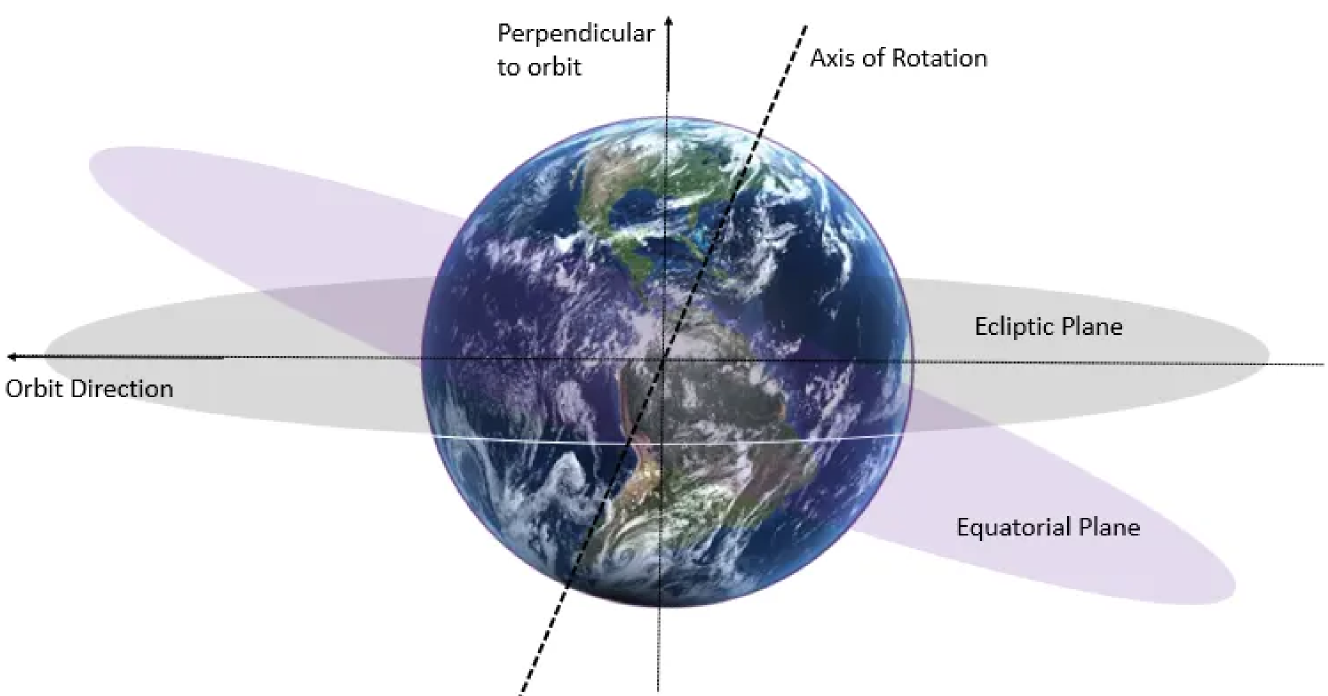
Earth-Centered Inertial (ECI) Frame:



As the name implies, this frame is inertial, meaning it has negligible acceleration (it can have a constant velocity though) and is non-rotating. Newton's laws hold for inertial frames, making them convenient when working with orbits. One of the most common inertial frames used for Earth-orbiting satellites is the J2000 frame. Using the J2000 frame as an example, here is how inertial frames can be defined:

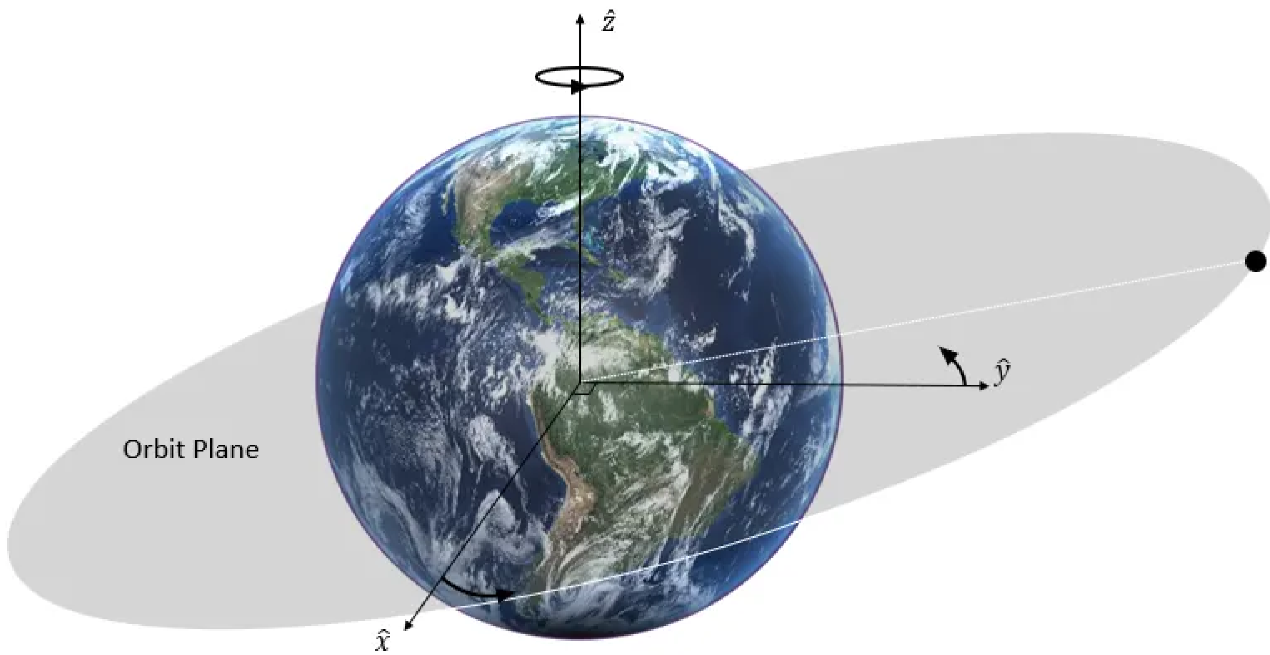
- *Origin*: Fixed at the center of the Earth
- *X-axis*: Points towards the vernal equinox (where the equatorial and ecliptic plane intersect) at epoch J2000
- *Y-axis*: Perpendicular to *X* and *Z* axes (*Z* crossed with *X*)
- *Z-axis*: Earths' rotation axis at epoch J2000

There are some terms here that you may not know, so let me clarify. Epoch J2000 is a standardized point in time (about 12:00p, January 1, 2000 GMT) defined precisely at Julian date 2451545.0 Terrestrial Time. I'll let you do a little research into Julian dates since that's not the topic at hand. The equatorial plane is the plane passing through the equator of the Earth. The ecliptic plane is the plane containing the Earth's orbit around the Sun. See the below diagram to help visualize that.



Applications: astrodynamics, interplanetary flight (not necessarily the ECI frame, but another inertial frame)

Earth-Centered, Earth-Fixed (ECEF) Frame:



The ECEF frame is also has its origin at the center of the Earth, like the ECI frame, but its unit vectors are fixed in the planet. This means the frame rotates with the planet at approximately 15˚ per hour (360˚ over 24 hours). This rotation makes this frame of reference non-inertial.

- *Origin*: Fixed at the center of the Earth
- *x-axis*: Points towards the intersection of the equatorial plane and the Greenwich Meridian
- *y-axis*: Perpendicular to *x* and *z* axes (*z* crossed with *x*)
- *z-axis*: Points northward along the Earth's axis of rotation

Applications: satellite ground tracking, global positioning systems (GPS)

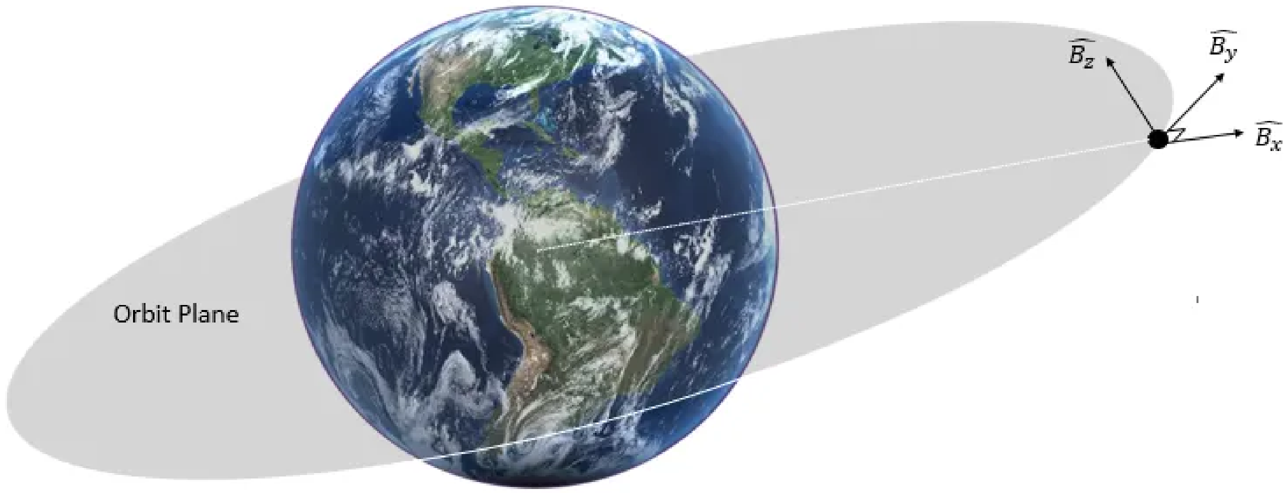
Local Vertical, Local Horizontal Frame:

There are likely other names for this reference frame, but in my schoolwork, we called it the local-vertical local-horizontal frame, or the the LVLH frame. This frame is not inertial since it is defined with its origin at the object of interest, which is orbiting, or rotating, about our primary mass. The object is likely accelerating and decelerating as well.

- *Origin*: Fixed at the center of the object
- *r-axis*: Points directly away from the primary mass center (local vertical)
- *θ-axis*: Perpendicular to *r* and *h* axes (*h* crossed with *r*)
- *h-axis*: Points in the direction that is perpendicular to the orbit plane

Applications: astrodynamics, two-body problem, rocket launches

Body Frame:

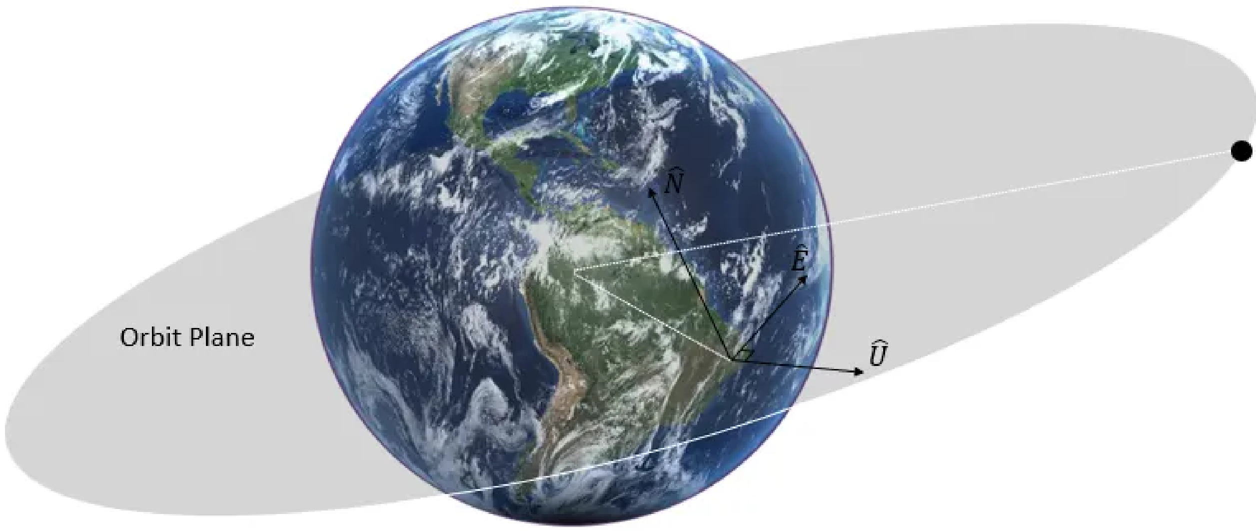


The body frame is probably one of the more important frames on this list. Its utilized to define how a spacecraft is oriented. The unit vectors are fixed to the body meaning they rotate or spin as the object of interest does. This means you can track where your object is pointing, or how it is oriented. For example, imagine you have a spacecraft with solar panels. Naturally, you want those pointing towards the Sun. You can check your body frame vectors and determine if they are, or if you need to make a correction.

- *Origin*: Fixed at the center of the spacecraft (or other body of interest)
- *Bx-axis*: Points towards the nose of spacecraft
- *By-axis*: Points to the right side of the spacecraft (when looking in the direction of *Bx*) perpendicular to *Bx*
- *Bz-axis*: Points to the bottom of the spacecraft. Perpendicular to *Bx* and *By* axes (*Bx* crossed with *By*)

Applications: defining spacecraft orientation, rotational dynamics of spacecraft

Topographical Frame:



The topographical frame is defined much different than the other four reference frames. Here you can see that the frame's origin is at the surface of the planet. One of the more typical topographical frames is the NEU or North-East-Up frame, but there are plenty of others. It is a non-inertial frame that rotates on the surface of the planet.

- *Origin*: Fixed at or near the Earth's surface
- *N-axis*: Points North towards the axis of rotation
- *E-axis*: Points East, perpendicular to *N* and *U* axes (*N* crossed with *U*)
- *U-axis*: Points up, or parallel to the gravity gradient

Applications: rocket launch tracking, telecommunications stations, landers or rovers

As you can see, there are a few overlaps between these reference frames in how they are defined and their possible applications. These frames can also be adjusted to better suit your problem. The unit vectors don’t necessarily need to be pointed the directions I have drawn them as long as they are a right-handed system. Hopefully this helped explain one of the most important concepts needed for orbiting bodies, the reference frame.

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Thanks for reading! Feel free to comment, ask questions, etc., and if you found anything interesting or learned something new, please follow and clap for the article!

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References:

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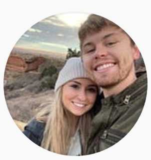

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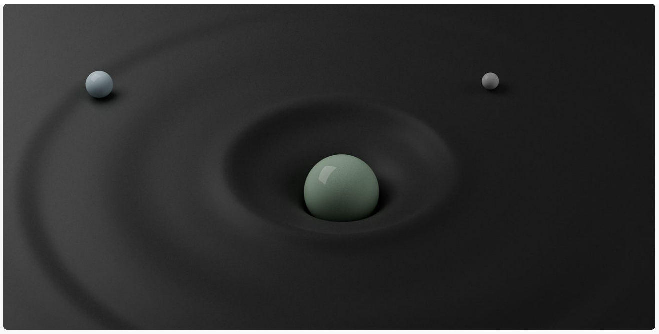

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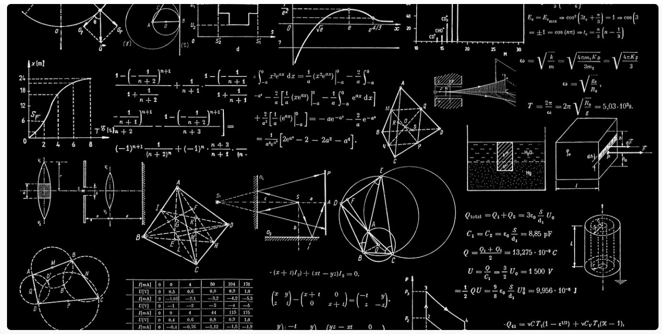

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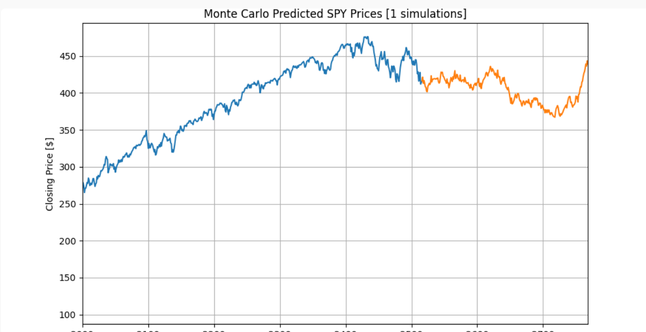

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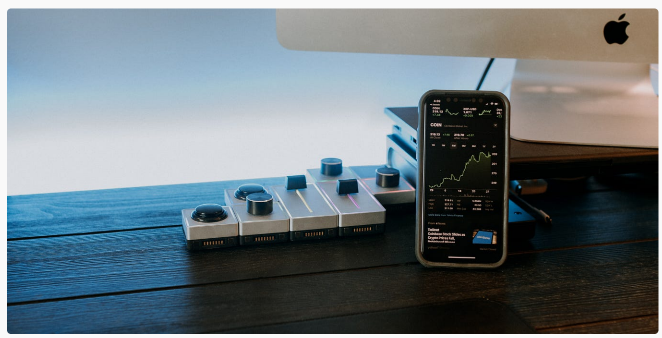

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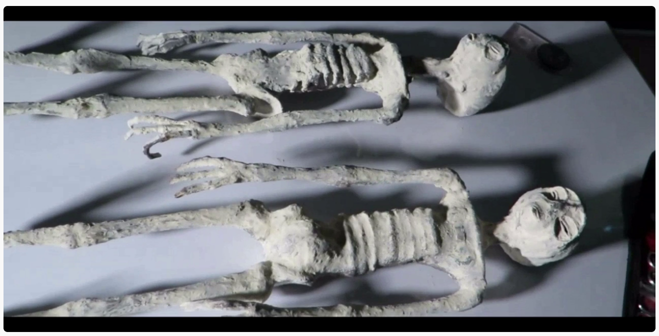

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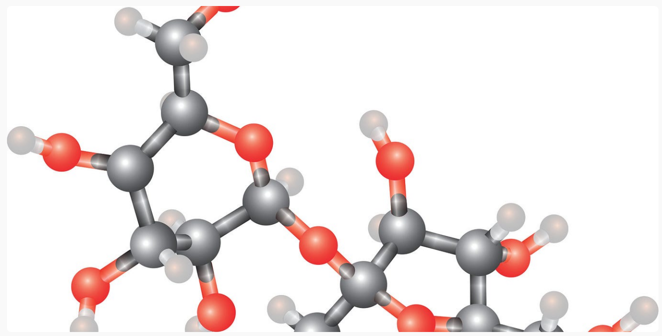

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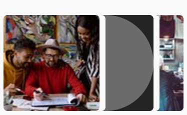

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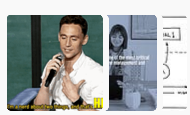

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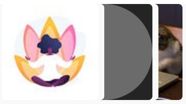

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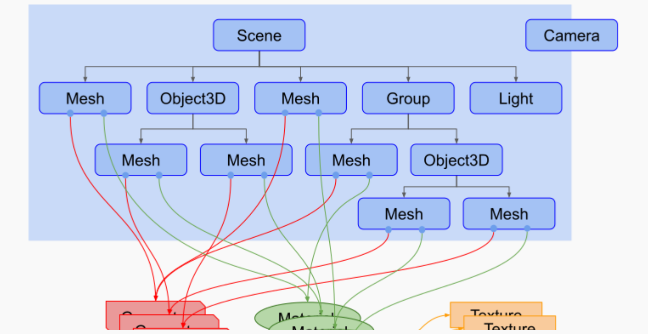

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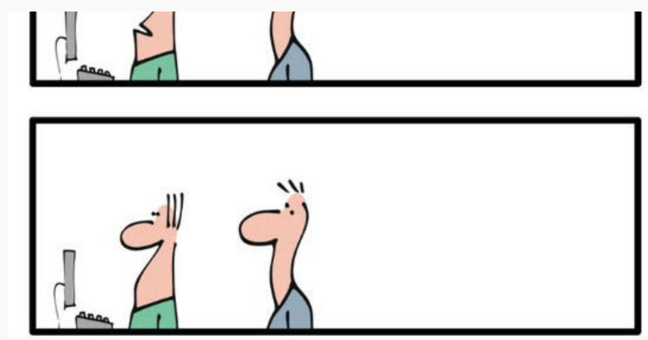

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