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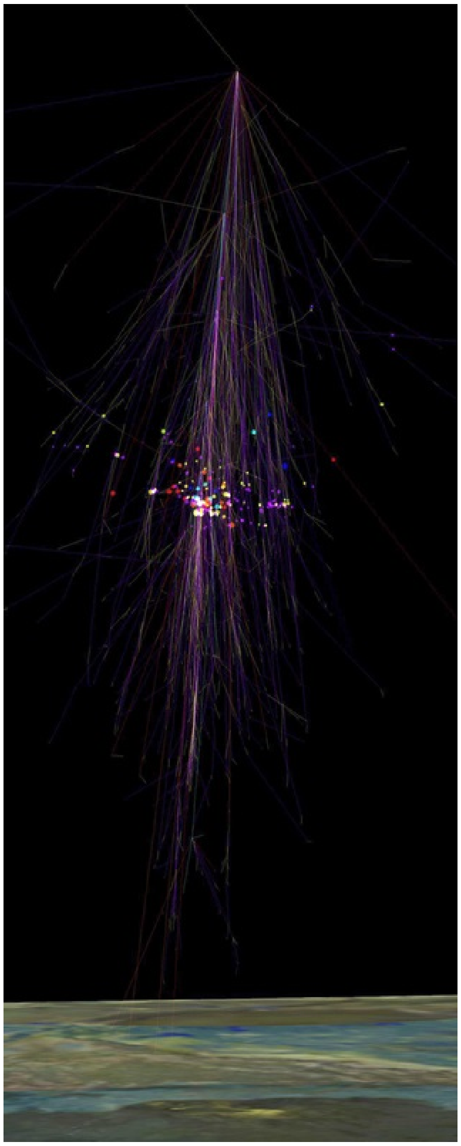
COSMIC MISHAPS:
HOW COSMIC RAYS CAN DISRUPT YOUR DESIGN



Your electronic design is haunted by intergalactic gremlins. The Earth is constantly bombarded by high-energy particles from stars all throughout the galaxy. These charged particles consist of subatomic particles, such as neutrons, electrons and muons, and fully-ionized atomic nuclei traveling at relativistic speeds. When these cosmic rays strike the oxygen and nitrogen molecules in our atmosphere, they leave a shower of high-energy photons and elementary particles in their wake.

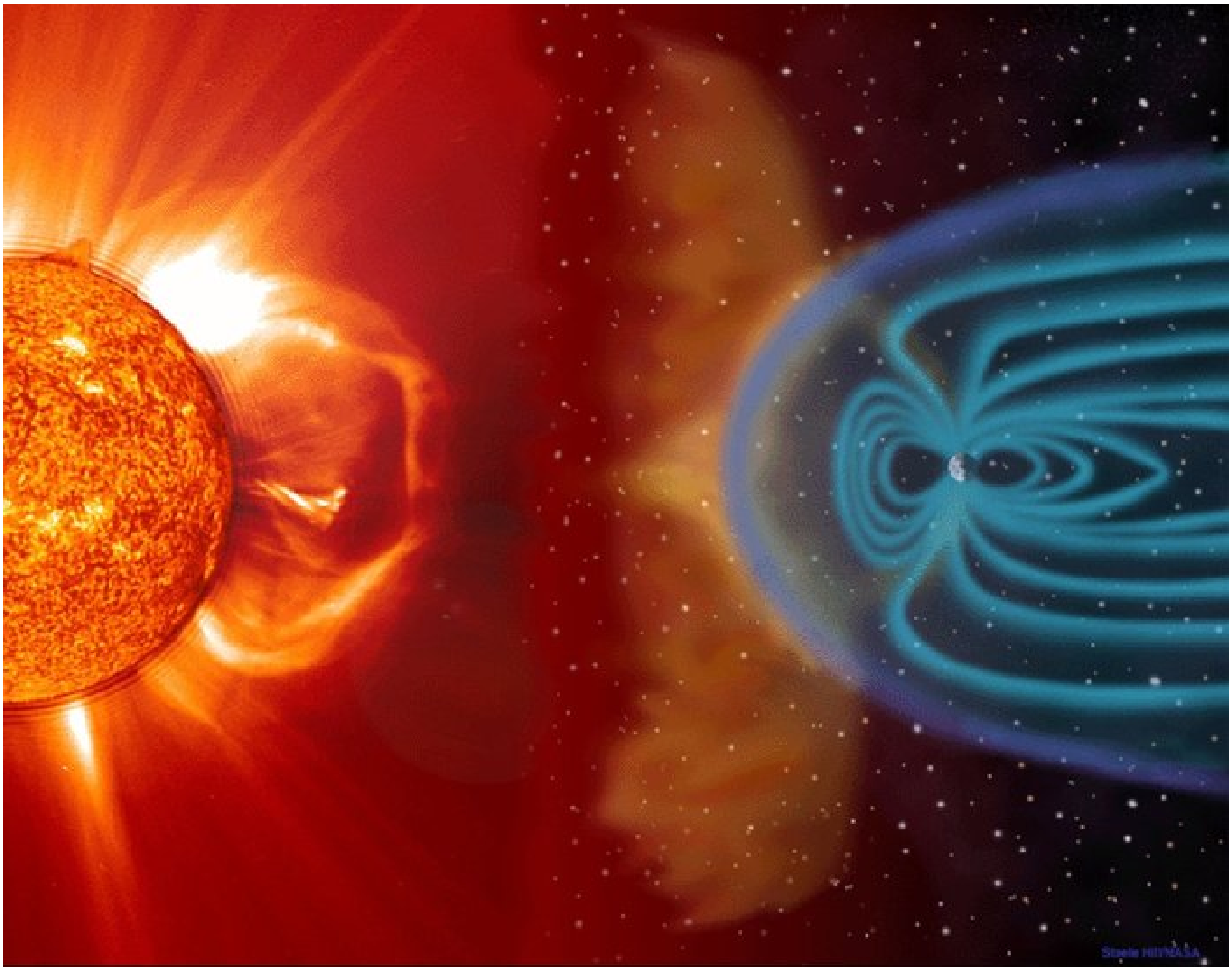
A portion of those high energy particles can make it all the way through the atmosphere to the surface of the Earth. If a cosmic ray, or one of its byproducts, passes through your printed circuit board, it can either damage PN-junctions, temporarily change the logic-level thresholds of digital inputs and digital outputs, and temporarily or permanently flip bits and entire words of memory in your microprocessor or microcontroller.

While the events are rare on the surface of the Earth, the consequences of a Cosmic Ray strike can be deadly. Cosmic Rays are thought to be responsible for lightning strikes, airplane accidents, runaway automobiles, and perhaps even erroneous election results.

Left: This artistic rendition of a particle shower imagines the secondary particles produced by a helium nucleus when it collides with air molecules: Cosmus (University of Chicago/Randy Landsberg/Mark Subba Rao/Dinoj Surendran)/Sergio Sciutto

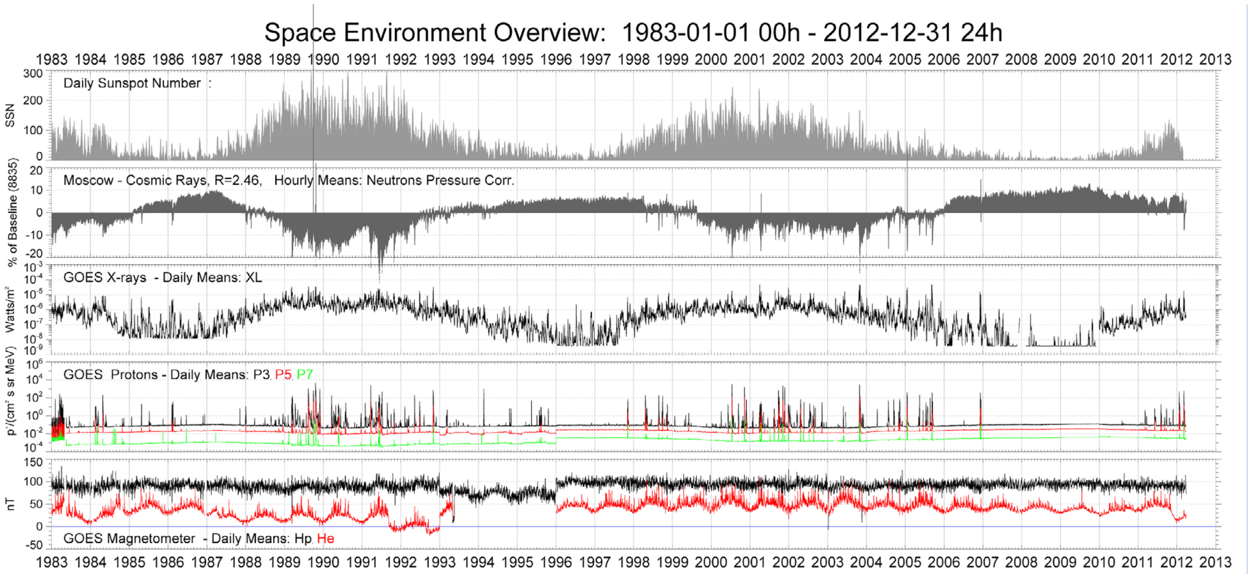
COSMIC RAY INCIDENCE

Cosmic rays are charged and uncharged particles that pass through the Earth's magnetic fields. The magnetic fields that surround Earth capture and redirect charged particles into pseudo-toroidal regions high above the surface of the Earth. While in these "Van-Allen-Belt" toroids, the particles are accelerated to relativistic speeds. Trapping particles is great news for the health of terrestrial-based electronic designs. But it is quite obviously bad news for spacecraft and astronauts that might have to operate through these regions of space.



This artistic interpretation shows an image of the Sun's corona combined with the Earth's magnetosphere is provided by the [European Space Agency / Nasa]

The cosmic ray flux on the Earth's surface is influenced by a variety of factors, including the 11-year solar cycle, solar flares, and extra-solar events such as supernovae, pulsars, and gamma-ray bursts.



30-year cosmic ray flux from the National Geophysical Data Center

Without the Earth's atmosphere to absorb cosmic rays, satellites and interplanetary probes are perpetually bombarded by high-energy, charged particles. This harsh-environmental condition requires specially engineered integrated circuits. Fortunately, a great deal of hard-won experience has taught us what to expect in space, and that information can be generalized for experiences closer to the surface of the Earth.

Spacecraft electronics will see the greatest number of impact events, followed by airplanes, and high-altitude and high-latitude installations. No part of the Earth is so remote that impacts do not happen. Only by burying your circuit board assembly deep underground can you gain enough shielding to avoid Cosmic Rays. As electronic packages shrink, the chances of an impact decrease. But as operating voltages decrease, the chance of a failure caused by a cosmic ray increase.

HOW COSMIC RAYS MIGHT IMPACT YOUR NEXT AEROSPACE OR HIGH-ALTITUDE ELECTRONIC CIRCUIT BOARD ASSEMBLY

Cosmic rays are not the only source of terrestrial radiation. Anytime an atom / molecule can emit mass or energy and enter a lower energy state, the laws of physics say it will do just that. Nuclear power and research engineers design electronics for high-radiation environments, as do medical-device design engineers, and even energy company engineers who design downhole sensor platforms, where gamma-ray sensors log radiation levels and detect shale deposits.

So we will start with how radiation affects your printed circuit board design, and later discuss some mitigation techniques.

EVENT CLASSIFICATIONS

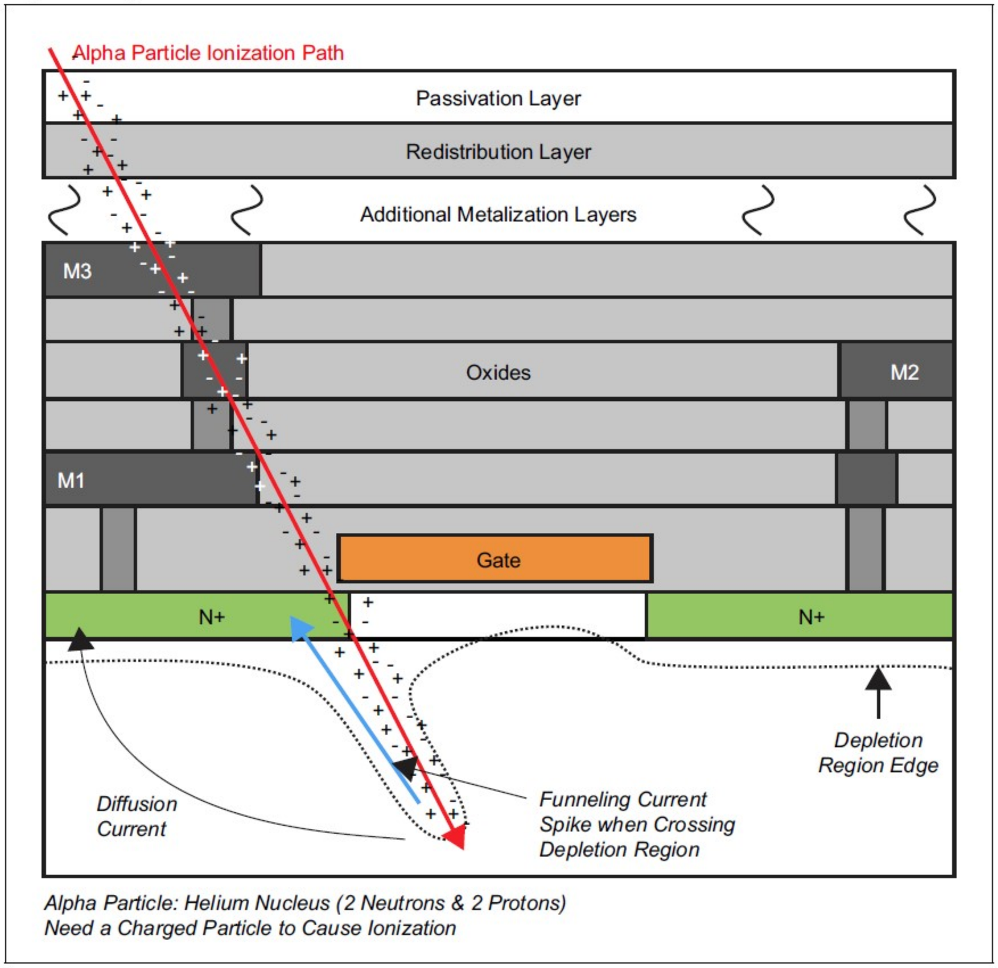
From the study of radiation effects on electronic designs, scientists have grouped the following failures, called *Soft Errors*. Here is a partial list.

Single Event Effects

- Single-Event Transient effects temporarily change the output of the device. This provides false analog readings and incorrect digital logic-levels.
- Physics Single-Bit Upset causes a failure in a single bit of a memory cell.
- Physical Multibit Upset changes the value of more than one memory bits. Anywhere from two to hundreds or even thousands of bits might be affected.
  - Multi-Bit Upsets occur when more than one bit in a word is affected.
  - Multi-Cell Upsets occur when bits from multiple words are affected.
- Single-Event Stuck Bits describe when a bit is permanently flipped.
- Single-Event Latchup / Functional Interrupt occurs when control logic is affected to the point that the device no longer functions. If there is no permanent damage, power cycling the device and perhaps rewriting data to memory should fix the error.
- Catastrophic part failures occur when a high-energy particle creates a conductive path through a transistor. This can cause Gate Latchup, Gate Burnout, and Gate Rupture, conditions that might require device replacement.

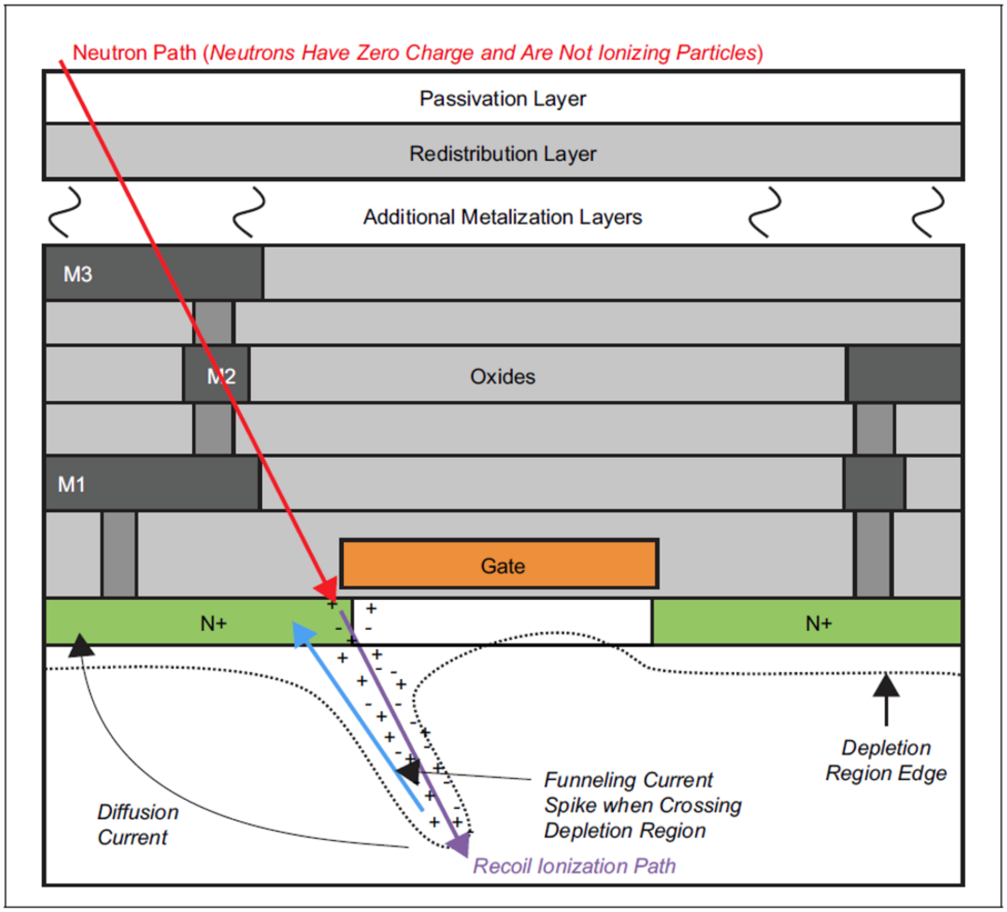
Charged particles create ionization paths with free electrons and holes in a semiconductor. Often, the electrons and holes recombine, and the device returns to its previous state. If the path of the particle is through the depletion region of an NMOS or PMOS transistor, the impact can change the state of the storage element.[1] If the path of the particle is through an insulator, it can free electrons and leave positive charged ions in its wake. This has the effect of change logic levels as well as logic-threshold voltages.

[1] Sydow, M. (n.d.). WP-01206-1.0 White Paper - intel.com. Retrieved October 3, 2019, from https://www.intel.com/content/dam/www/programmable/us/en/pdfs/literature/wp/wp-01206-introduction-single-event-upsets.pdf.



The image above is from the Altera WP-01206-1.0 White Paper entitled "Introduction to Single-Event Upsets." The paper states *"when the path crosses the depletion region underneath a drain-gate-source region the electrons it creates can be quickly attracted to a higher voltage NMOS drain diffusion, which sometimes results in the change of state of a storage element. Similarly, for PMOS transistors, the holes can be quickly attracted to a lower voltage PMOS diffusion. Even if the ionization path is nearby, the diffusion path of electrons or holes could also result in a storage element upset as well."*

But neutral neutrons can cause damage as well -- either by colliding with molecules and creating secondary charged particles, or by creating electron-hole pairs in a gate-source region or p-n junction. Then, as in the previous example, NMOS and PMOS transistor storage elements can change state.



The image above is from the Altera WP-01206-1.0 White Paper entitled "Introduction to Single-Event Upsets." Once the particle creates an electron-hole pair in either a PMOS or NMOS transistor, the free charges can disturb the proper function of the transistor.

COSMIC RAY IMPACTS AND FAILURES IN TIME

It is impossible to know exactly when and where a Cosmic Ray will strike an integrated circuit on your printed circuit board. But enough cosmic ray data has been collected at the surface of the Earth to form models based on latitude, longitude, and altitude to come up with a decent estimate. For example, the neutron flux calculation at http://seutest.com provides the flux at different latitudes / longitudes / altitudes relative to New York City (a common reference location) where the neutron flux is 13 neutrons per square centimeter per hour. At an elevation of 5 miles, the flux increases to 1300 neutrons per square centimeter per hour.

If you know the size of the transistor gate/drain/source on the silicon die, and the size of a neutron, a Monte-Carlo integration can provide a probability of impact. Remember, smaller devices are less likely to be hit, but lower operating voltages and are more likely to be affected by a near-miss impact.

SOFT-ERROR RATES & FAILURES IN TIME

Since it is impossible to know exactly when or where a cosmic ray impact will occur, electrical engineers are left to statistics to determine the probability of impact. Manufacturers provide cosmic-ray data separate from terrestrial radiation sources in terms of Failure-in-Time, or FIT units. Memory suppliers provide data normalized to FITs/Mb or FIT/bit. One FIT unit is equal to one failure in 1-billion device hours (109 h.) That is not to say that a single device with a FIT of 1 will work for 1 billion-hours. Instead the metric is applied to large groups of products.

For example, if your circuit was installed on 500,000 cars and had a single transistor with a 14FIT rating, you could anticipate a failure every 6 days.

$$\frac{10^9 \text{ hours}}{14 \text{ failures}} \frac{1}{500000 \text{ devices}} \frac{1 \text{ day}}{24 \text{ hours}} = \frac{5.95 \text{ days}}{1 \text{ device failures}}$$

This might be acceptable for a fan on a air-sensor unit that measures cabin air quality. But it would be wholly unacceptable risk for a device that controls, say, the cars throttle on a Toyota Prius.

As another example, 700 FIT/Mbit might be an appropriate cosmic-ray induced soft-error rate for a plane flying at an altitude of 1.4 miles. How many SER events can be expected in 512 MByte (4.096x109 bits) of memory each month?

$$\left(\frac{700 \text{ FIT}}{10^6 \text{ bits}}\right)\left(\frac{1 \text{ failure}}{10^9 \text{ device hours}}\right)(4.096 \times 10^9 \text{ bits}) = 0.00287 \ \frac{failures}{hour} = 2 \ \frac{failures}{month}$$

Like everywhere else in electronics device manufacturer, “specmanship” has invaded rad-hard datasheets. So before you dismiss one electronics manufacturer for another, you should research how their electronics devices were tested. Were they accelerated or actual tests? How were the FIT values determined?

The JEDEC standard JESD89A “Measurement and reporting of Alpha Particle and Terrestrial Cosmic Ray Induced Soft Errors in Semiconductor Devices” details how to test and report the soft-error-rate of custom electronics designs. And it is important to note that radioactive decay, thermal neutrons, and contaminants can induce errors in addition to cosmic ray activity.

FIGHTING BACK AGAINST PHYSICS

Fortunately, many electronic devices have radiation hardened counterparts -- those are versions of the devices that have been engineered to be less susceptible to failure in the event that a high energy photon or particle strikes them. Unfortunately, radiation hardened devices usually come out months or years later than their non-hardened counterparts, if they come out at all.

So what can you do with commercial off-the-shelf (COTS) electronic components already available at your favorite distributor? You can usually improve your design.

Go through each part in your schematic and ask yourself "What happens if this particular component fails at the worst possible time? What happens if two electronic components fail at once?" Does it mean an airplane will fall thousands of feet in the air or perhaps crash? Does it mean a person can be electrocuted? Does it mean your firmware can be unlocked? Does it mean your ATM will spit out all its money? If so, you need to weigh the catastrophe against the cost of mitigating the failure.

Lower-Voltage Components are More Susceptible to Single-Event Upsets

Cosmic Rays don't arrive from the heavens with a single energy level. There is a spectrum of energies, and high energy cosmic-rays are less common than low-energy cosmic rays.

As electronics continue to shrink, chip designers are able to reduce the operating voltage of devices -- which makes them more energy efficient, and also more susceptible to the lower-energy cosmic rays.

As a charged particle travels through an insulator or semiconductor, it can liberate electrons and leave a trail of positively charged ions in its wake. These positive charges can shift the logic thresholds for a device.

That means, from a reliability standpoint, an integrated circuit that operates at 5.0 V logic will be less susceptible to a cosmic ray impact than one that operates at 1.8 V logic. The 5.0 V logic device might have logic thresholds of 1.5 V for logic-high and 3.5 V for logic-low, a potential difference of 2.0 V, while the 1.8 V device might have thresholds defined at 1.2 V for logic-high and 0.7 V for logic-low, a potential difference of only 0.5 V. Cosmic rays capable of generating that 0.5 V of electric potential are simply more plentiful than ones capable of imbuing 2.0 V in a design. The threshold differences are even smaller for <1 V electronic circuit designs.

Note though, that the voltage of many memory modules is internally regulated, so they will operate at the same fixed voltage regardless of the input voltage. In that case, the supply voltage does not affect the soft-error rate due to cosmic rays.

SENSORS AND MICROCONTROLLERS OPTIONS

Critical sensors and microcontrollers can be installed in triplicate to provide redundancy. Things break, wires rub, rats chew cabling. Your sensor system is likely to be damaged by something far less exotic than a cosmic-ray, but a redundant design philosophy will protect against a wide assortment of failures. As a recent example, redundant sensor design and programming would have allowed the flawed Boeing 737-Max aircraft to land after one of its air-speed sensors failed.

A cosmic ray is statistically likely to only ever strike one of the three devices at a time, so two devices should have identical results -- the third device's results can be ignored. A Power-Management-IC can then independently cycle the power of the malfunctioning sensor/microcontroller to attempt to return it to service. If the third device continues to return flawed results after power cycling, it can be shut down and ignored until it is replaced. In fact, the design can continue to function until the last two sensors fail to agree. At that point, you presumably wouldn't know which sensor to trust and the electronic circuit would require repair or replacement.

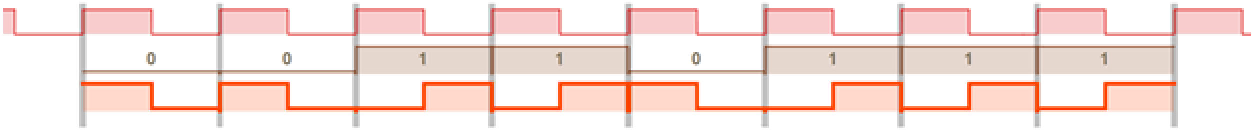
Intelligent Firmware

If your design is less critical, and you cannot afford to include redundant sensors, can you run your data through a computational sanity-check? A digital filter might identify and reject results that are physically impossible, or statistically unlikely from a sensor. For example, a temperature sensor that steadily increases by 2 °C/min over the course of 10 minutes is probably unlikely to suddenly increase by 4098° C/min at the next measurement interval. Does your microcontroller take the input value, no matter what it is, and act on it? Or can you implement programming safeguards to ensure that only reasonable values affect the state of your device?

Error Correction

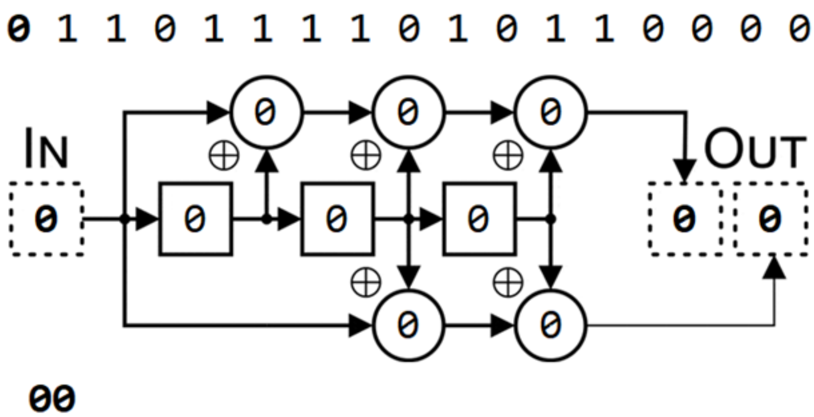
Electrical Engineers have invented a number of clever schemes that help engineers detect data transmission errors and, in many cases, correct them.

Manchester-encoding transmits each bit-value as two (or more) logic-levels separated by a transition rather than a single logic level. It can detect errors, and the receiver can request retransmission of the message.



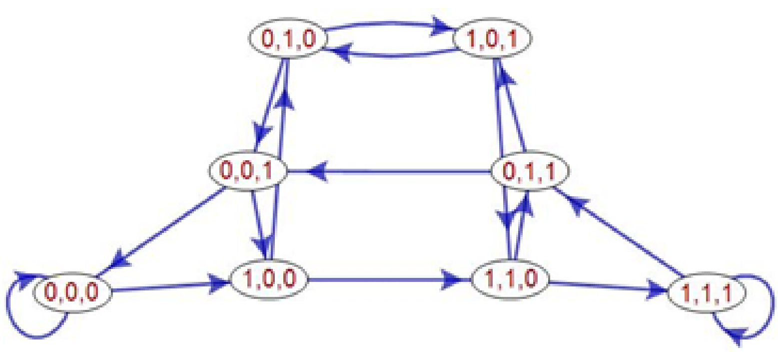
Forward Error Correction

Forward error correction uses a convolutional encoder that alters the original data in a reversible way. This technique creates a data sequence that is interlinks sequences of bits. The receiver of this data can correct one incorrect bit and detect two incorrect bits before requiring retransmission.



This animation of a convolutional encoder is from the article "What is Bluetooth 5? Learn about the Bit Paths Behind the New BLE Standard" at the website AllAboutCircuits.com[2]

Since the data output depends on data previously entered into the state-machine, only certain states are accessible from the previous one. This is what allows the "Forward Error Correction" to occur.



Each state can transition to only two other states. By keeping track of the data, and the allowable states, the receiver can detect when invalid data has entered the data stream. This state diagram is courtesy AllAboutCircuits.com

There are other error detection and correction schemes out there.

[2] https://www.allaboutcircuits.com/technical-articles/long-distance-bluetooth-low-energy-bit-data-paths/

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SUMMARY

Cosmic-Rays are not likely to impact your system, but they are possible. As you get your design ready for market, be sure to consider the possible failure modes and what they might mean to the safety and longevity of your product.

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