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Risk Analysis of Solar Photovoltaic Systems

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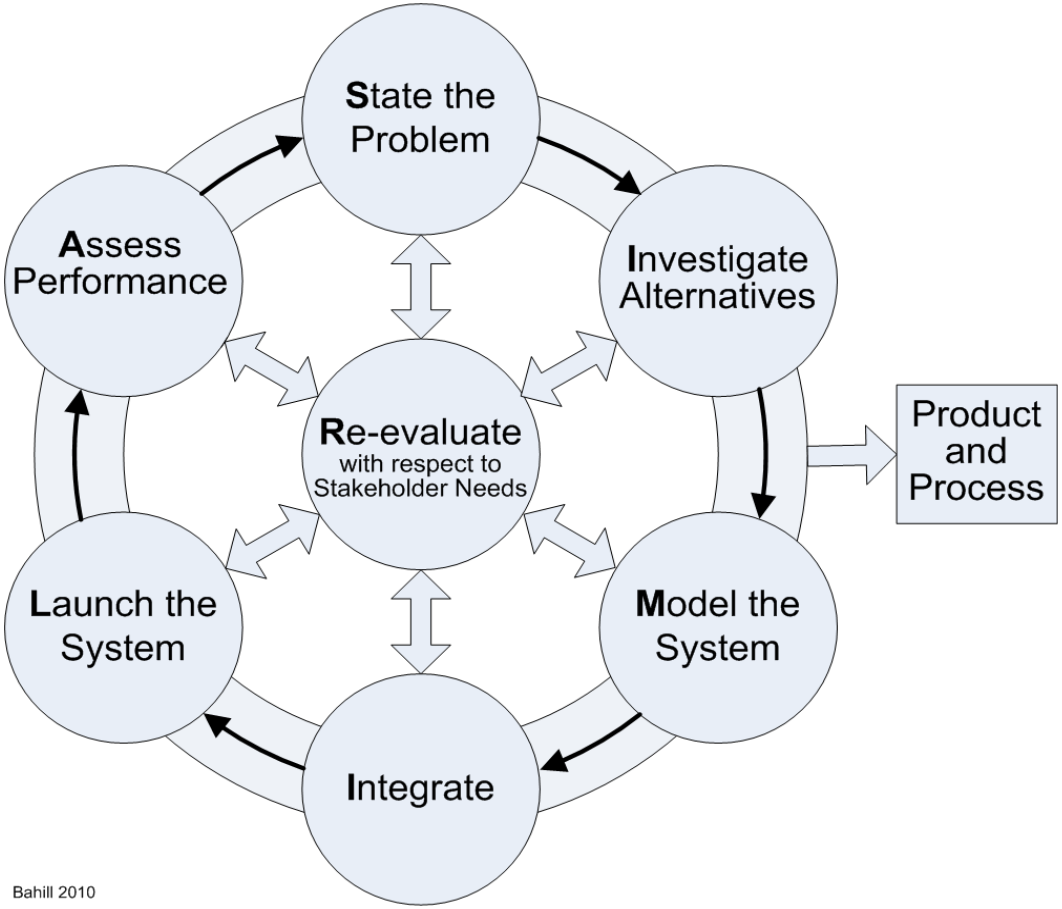
- Take 200 copies of Table 2 and Figure 2, double sided



Bahill 2010

circle

The SIMILAR Process

References

A. T. Bahill and E. Smith, An Industry Standard Risk Analysis Technique, *Engineering Management Journal,* **21**(4):16-29, 2009.

A. Chaves and A. T. Bahill, Locating Sites for Solar photovoltaic Panels, *ArcUser* (2010), 25-27, http://www.esri.com/news/arcuser/1010/files/solarsiting.pdf

A. Chaves and A. T. Bahill, Comparison of Risk Analysis Approaches and a Case Study of the Risk of Incorporating Solar Photovoltaic Systems into a Commercial Electric Power Grid, *Systems Engineering* **16**(4) (2013) DOI 10.1002/sys.21254, published on-line May 24, 2013.

Good Morning Philadelphia!

- When I was a boy digging a hole in the back yard, my Mother said to me, “If you dig that hole any deeper, you’ll end up in China!”
- Well that was in Tucson and we are now in Philadelphia.
- So, if you were to go outside right now and dig a *very* deep hole that went straight through the middle of the earth and came out on the other side, where would you be?


BarTucson
Philadelphia*
© 2013 Cnes/Spot Image
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
16°19'15.43" S 104°07'25.62" E elev -18832 ft
Eye alt 7281.12 mi

We lack knowledge about the world around us: therefore, we should do risk analyses.

Confirmation bias[1]

Humans pay attention to information that confirms their existing beliefs while they ignore information that contradicts their beliefs.

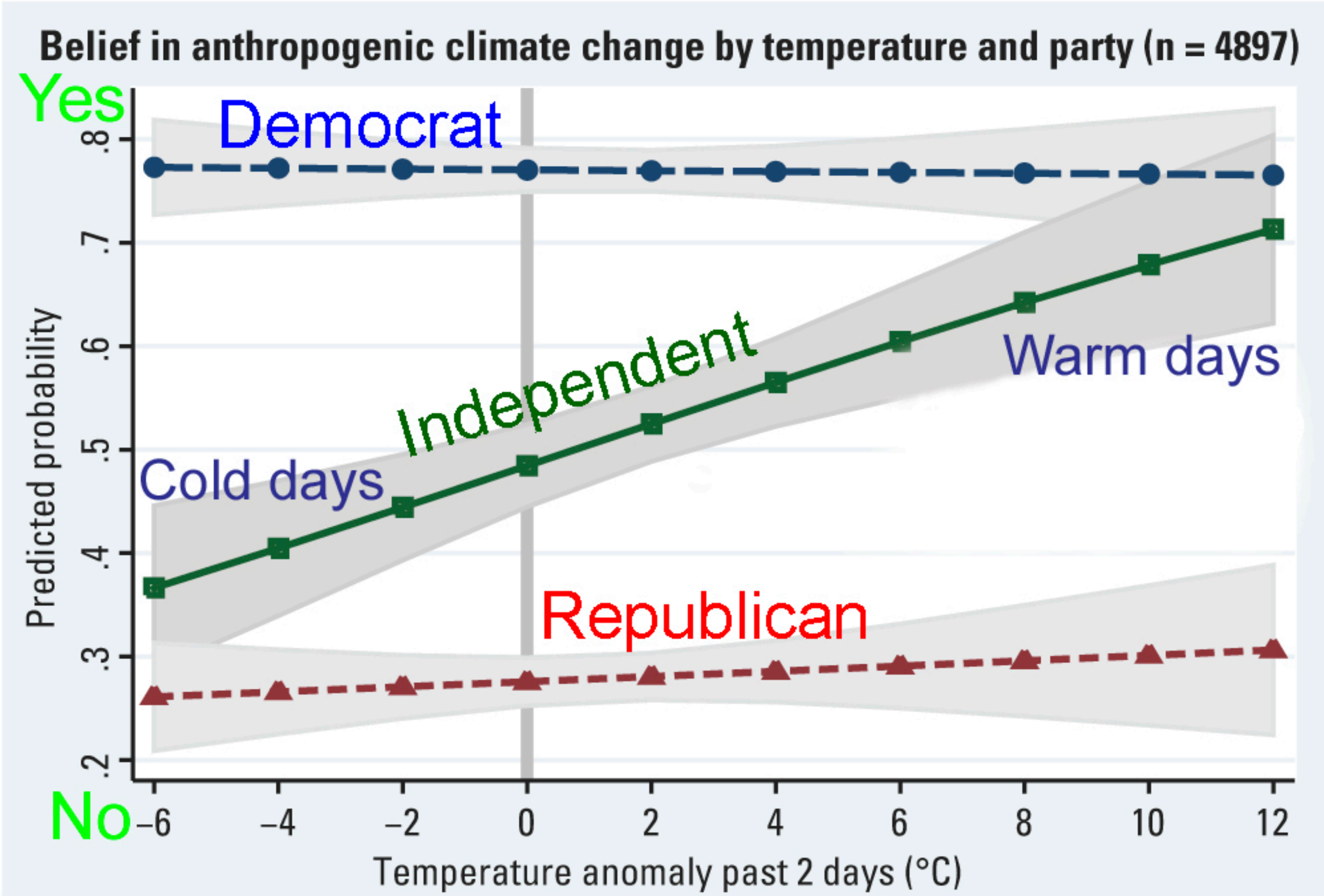
Confirmation bias$_2$

This is why mothers of terrorist murderers ignore DNA evidence and eye witness testimony and say, “My boy is innocent. He is a good boy: he would never have killed all those people.”

This is why people who think that they have infallible memories and perfect recall focus on instances when they correctly recalled events and facts, while they ignore instances when they forgot something.

Our knowledge of the world is usually wrong: therefore, we should do risk analyses.

Is global climate change "caused mainly by human activities?"



Lawrence Hamilton, University of New Hampshire, Durham, www.sciencemag.org, *Science* **339** February 1, 2013 p. 496

Our world is uncertain: therefore, we should do risk analyses.

First usage

"Fear of some harm ought to be proportional not only to the magnitude of the harm, but also to the probability of the event."

Logic, or the Art of Thinking

Arnauld and Nicole

1662

Definition

Risk is an expression of

- the potential harm or loss
- to a system being designed and its primary actors
- associated with its operation in a known but uncertain environment
- throughout its total life cycle.

Measure of risk

The measure of risk is the severity of the consequences times the frequency (or probability) of occurrence.

Because humans evaluate probabilities poorly, we will use frequency of occurrence.*

Humans evaluate numbers poorly

What is the missing term in this sequence?

1, 1, 1, 1, 1, 1, 1, 1, 1, 1,

1, 1, 1, 1, 1, 1, 1, 1, 1, 1,

1, 1, ?, 1, 1, 1

The missing term is 2

This is a listing of the number of syllables in each letter of the English alphabet.

The letter w is the only letter with two syllables.

Risk equations

$$\text{Risk} = \text{Severity of Consequences} \times \text{Frequency of Occurrence}$$

$$\text{Risk} = \text{Severity of Consequences} \times \text{Likelihood of Occurrence}$$

$$\text{Risk} = \text{Severity of Consequences} \times \text{Estimated Probability}$$

$$\text{Risk} = \text{Severity} + \text{Probability}$$

$$\text{Risk} = \text{Severity} + \text{Probability} - (\text{Severity} \times \text{Probability})$$

$$\text{Risk} = \text{Severity} \times \text{Probability} \times \text{Difficulty of Detection}$$

$$\text{Risk} = \text{Severity}^2 \times \text{Probability}$$

$$\text{Risk} = \text{Severity} \times \text{Exposure}$$

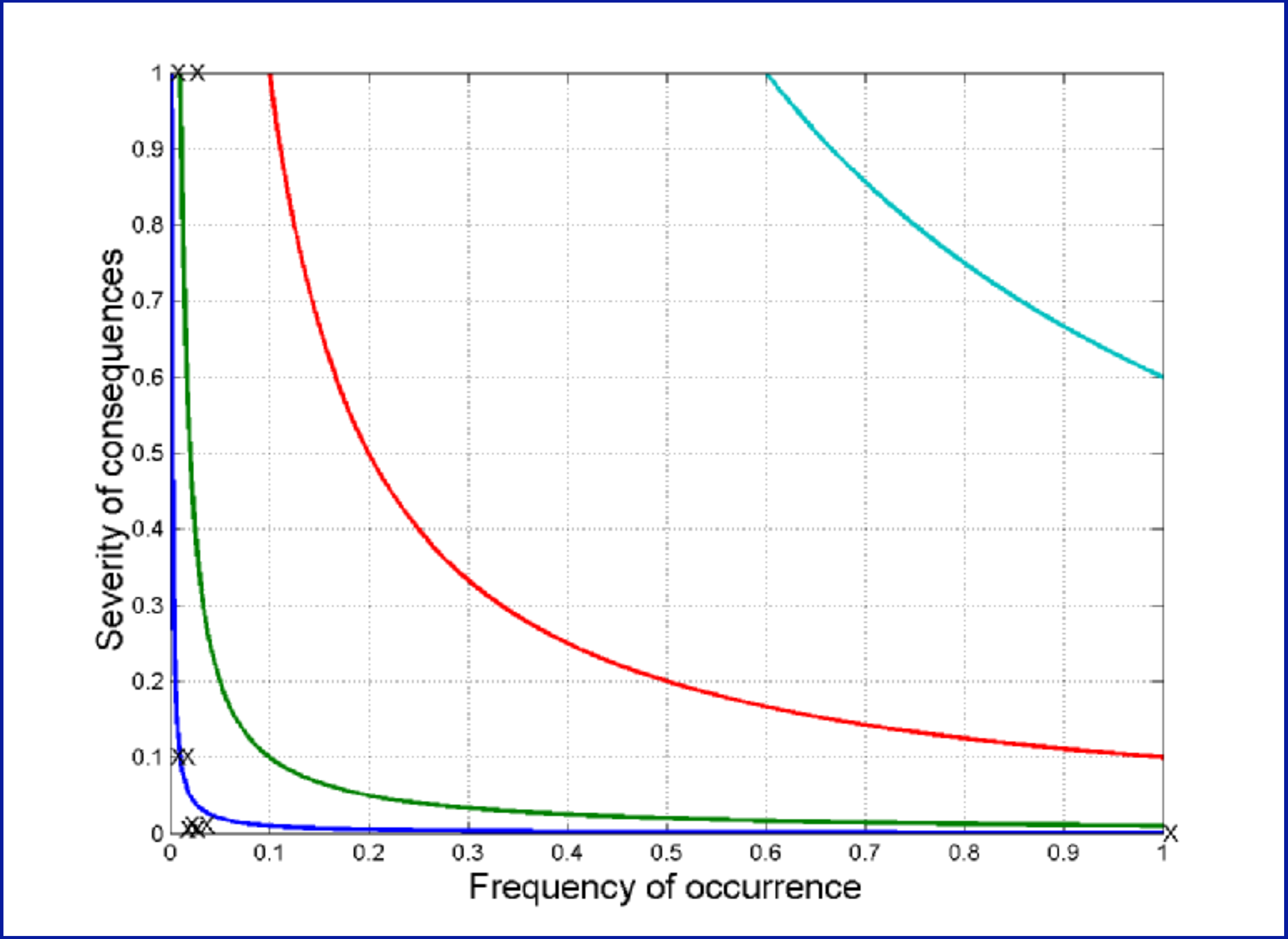
We will use

$$\text{Risk} = \left(\text{Severity of Consequences}\right)^{wt_s} \times \left(\text{Frequency of Occurrence}\right)^{wt_f}$$

An algorithm for computing severity values

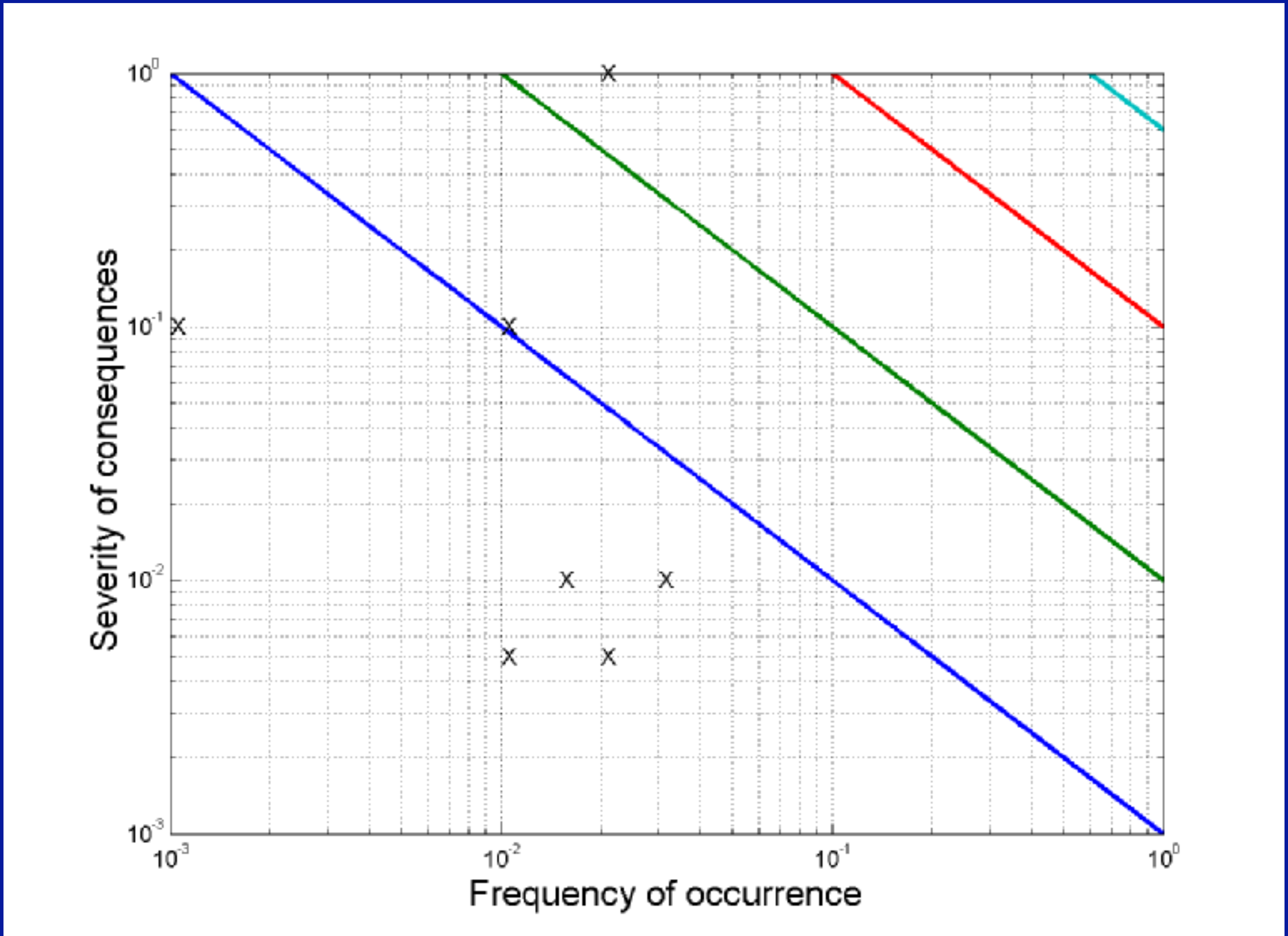
1. Assign a frequency (F_i) to each Failure event.
2. Find the Failure event that has the most severe consequences, call its value S_{worst}.
3. For each Failure event ask, “How many of these failures would be equally painful to one of the Worst?” Call this N_i
4. Compute the severity for each Failure event as $S_i = S_{worst} / N_i$
5. Normalize the severity values so that their range equals the range of the frequency values.
6. Compute the estimated risk.

Linear axes

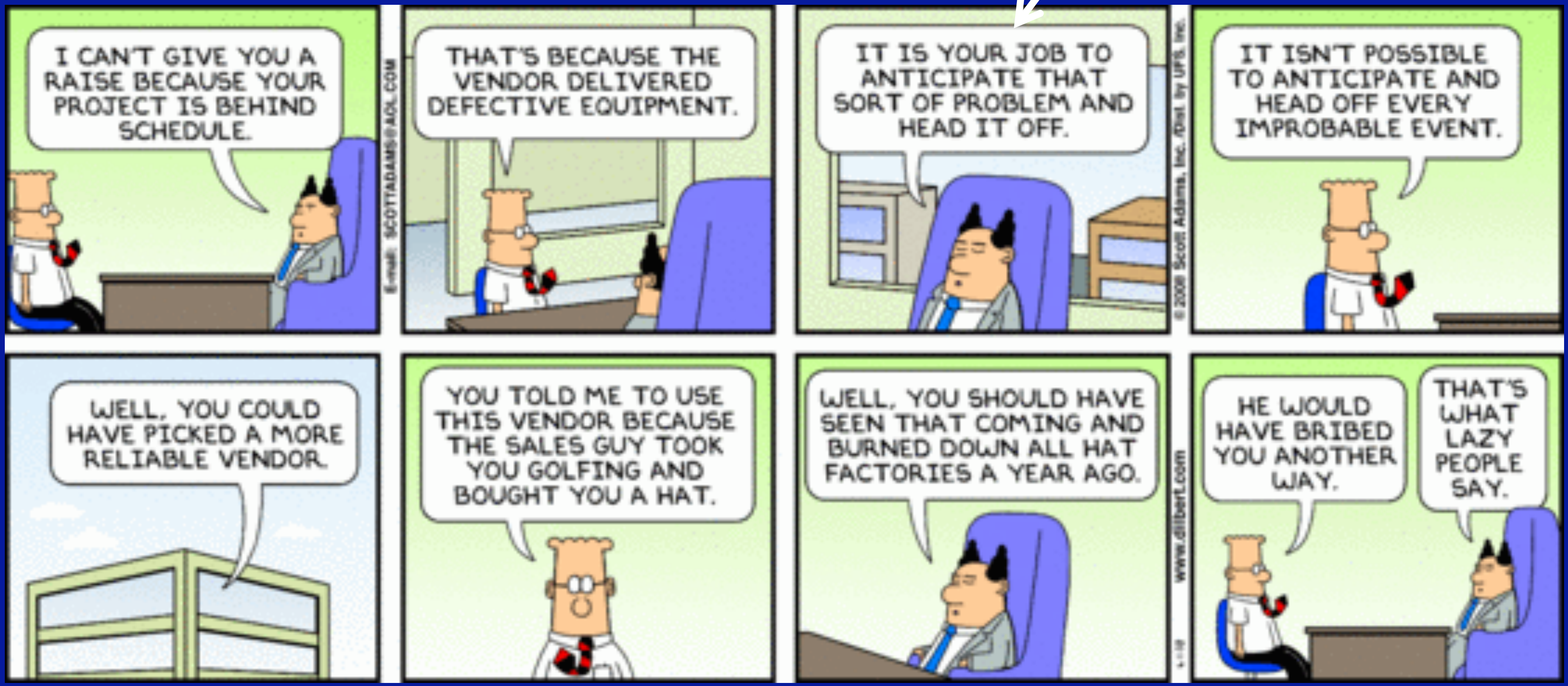


Severity of consequences
Frequency of occurrence
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Logarithmic axes



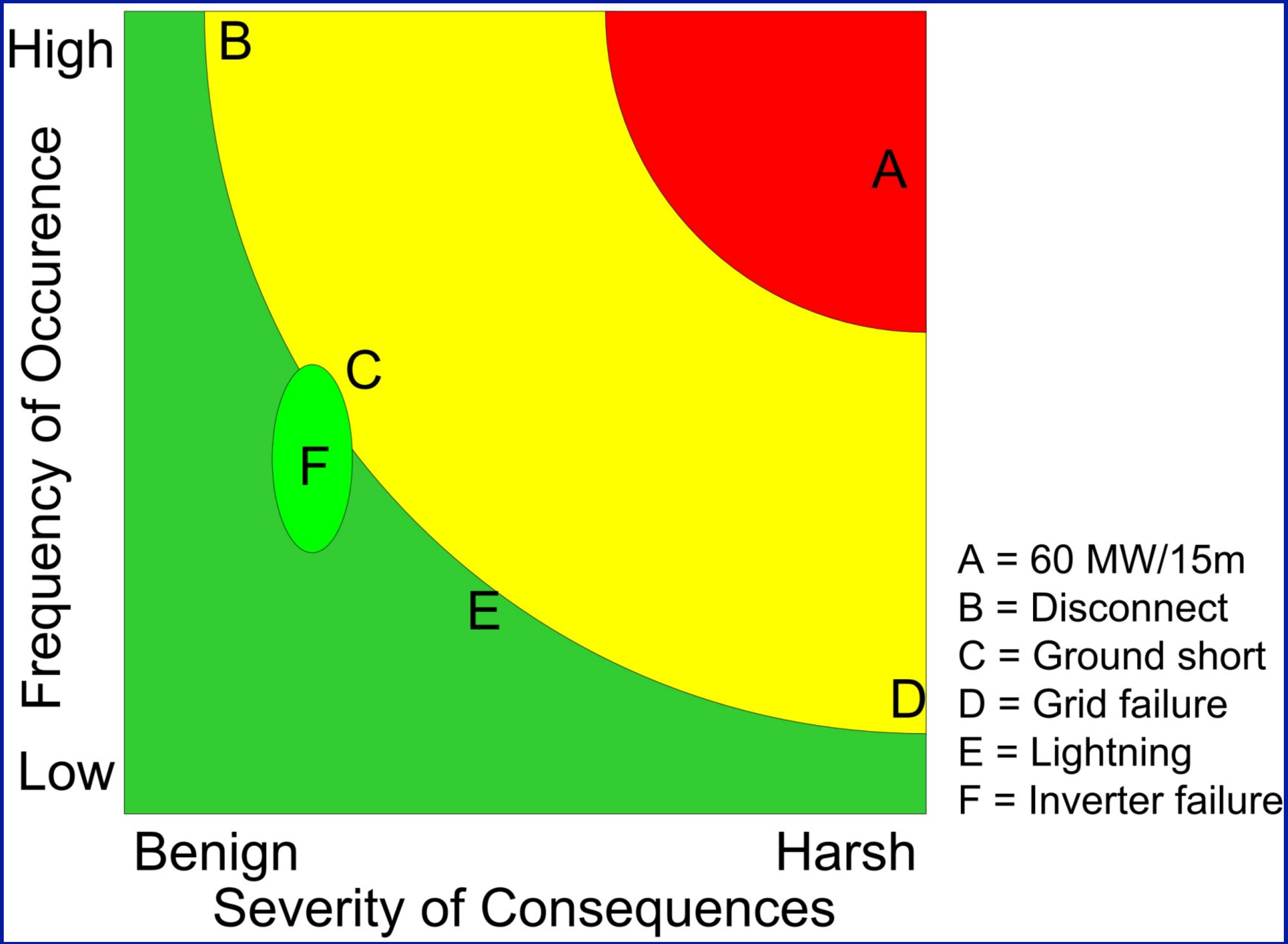
A risk analysis



TEP's paramount risks

Potential Failure Event	Consequences	Frequency of Occurrence in the TEP control area (events per year)	Severity of Consequences	Estimated Risk, defined as frequency times severity	Identification Tag
Solar panel output drops by 60 MW in a 15-minute interval.	Power production plummets tripping breakers and leaving customers without electric power. Voltage and frequency on the grid could drop.	95	200	19,000	A
Feeder circuit disconnects from substation	Feeder circuit voltage could get out of phase with the grid.	330	1	330	B
Short to ground on distribution grid	Equipment could be damaged, particularly transformers and capacitor banks.	24	10	240	C
Western Power Grid fails	The western United States would be without electric power.	0.03	1,000	300	D
Lightning strikes the system	Components could be damaged and electric generating capacity would be reduced.	0.4	100	40	E
Failure of DC to AC inverters	The customer can no longer sell electricity to TEP	240	0.1	24	F

Project risk management*



Two schools of thought

Here are two common ways to plot the results of a risk analysis.

The ordinate axis is the *probability of occurrence* and rigorous statistics are used throughout. Yacov Haimes and the Society for Risk Analysis have many examples.

The ordinate axis is the *relative likelihood*. This is the type of risk analysis used in industry and in this paper.

Industry risk management tool$_1$

- The ordinate axis is *not* probability
- Probabilities cannot be calculated because of uncertainty and unknown unknowns
- This axis is labeled *relative likelihood*
  - relative because it concerns relationships between risks
  - likelihood not in the mathematical sense, but in the dictionary sense indicating risks that are most likely

Frequency of occurrence versus relative likelihood

If there are historical data for an event, then use the term frequency of occurrence.

Otherwise, when guessing the future, use the term relative likelihood.

Industry risk management tool$_2$

The relative likelihood estimates are conservative.

"If we built the system today, with lofty capabilities, without improving the design, doing nothing about this risk item and if the worst possible circumstances occurred, then what is the possibility that this risk item will harm us?"

The relative likelihood scale is not linear: a risk with a relative likelihood value of 0.8 is not considered twice as probable as one with a value of 0.4.

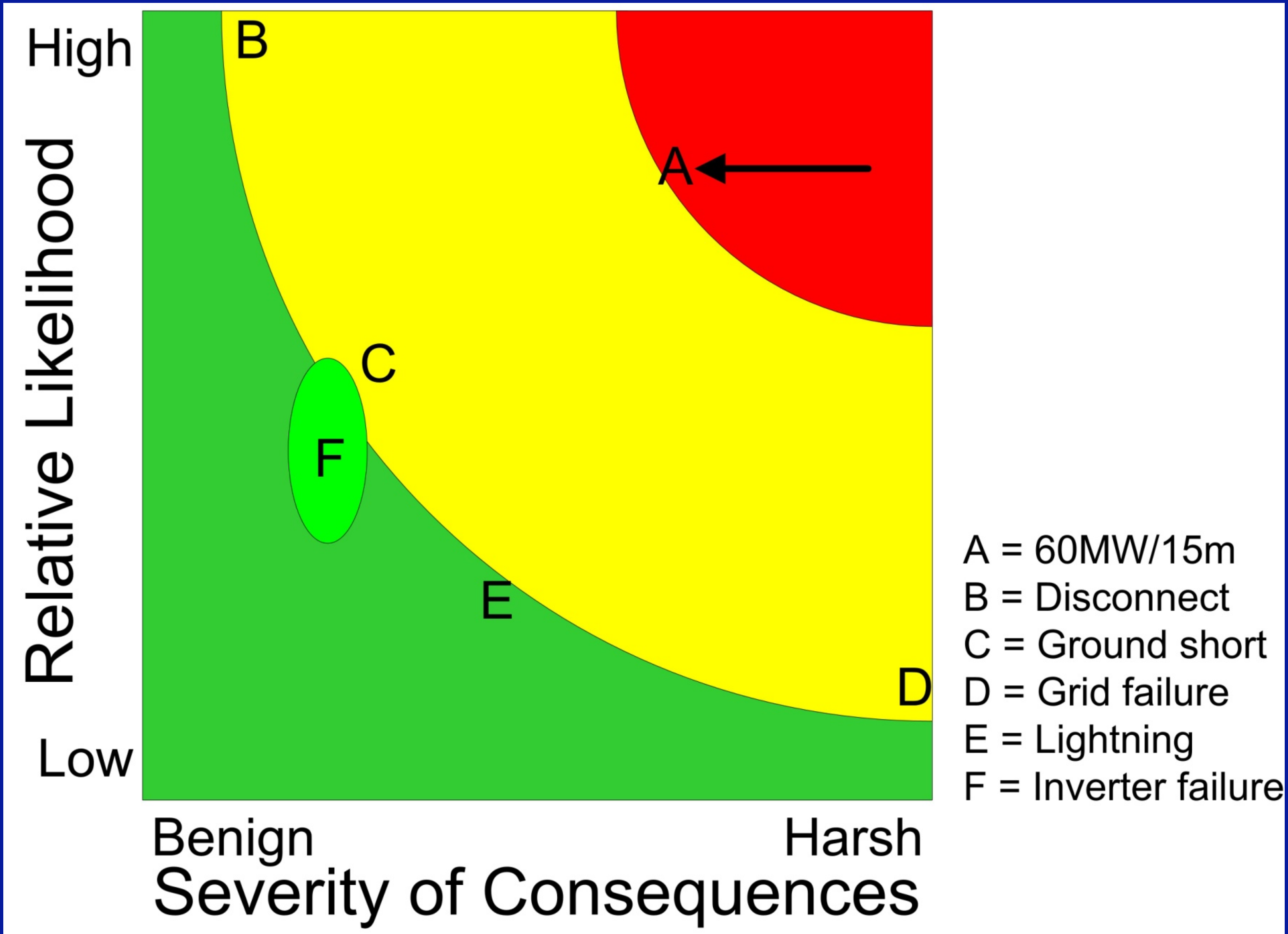
Tracking risk

The most important risks are put in the project risk register and are analyzed monthly and at all design reviews.

For our solar PV system, one of the biggest risks is that clouds cover the sun and generated electricity plummets by 60 MW in 15 minutes.

TEP mitigated this risk by installing rapid-start gas-turbine motor-generator sets. This ameliorated the risk and at the next review we presented the following risk chart.

Project risk after mitigation



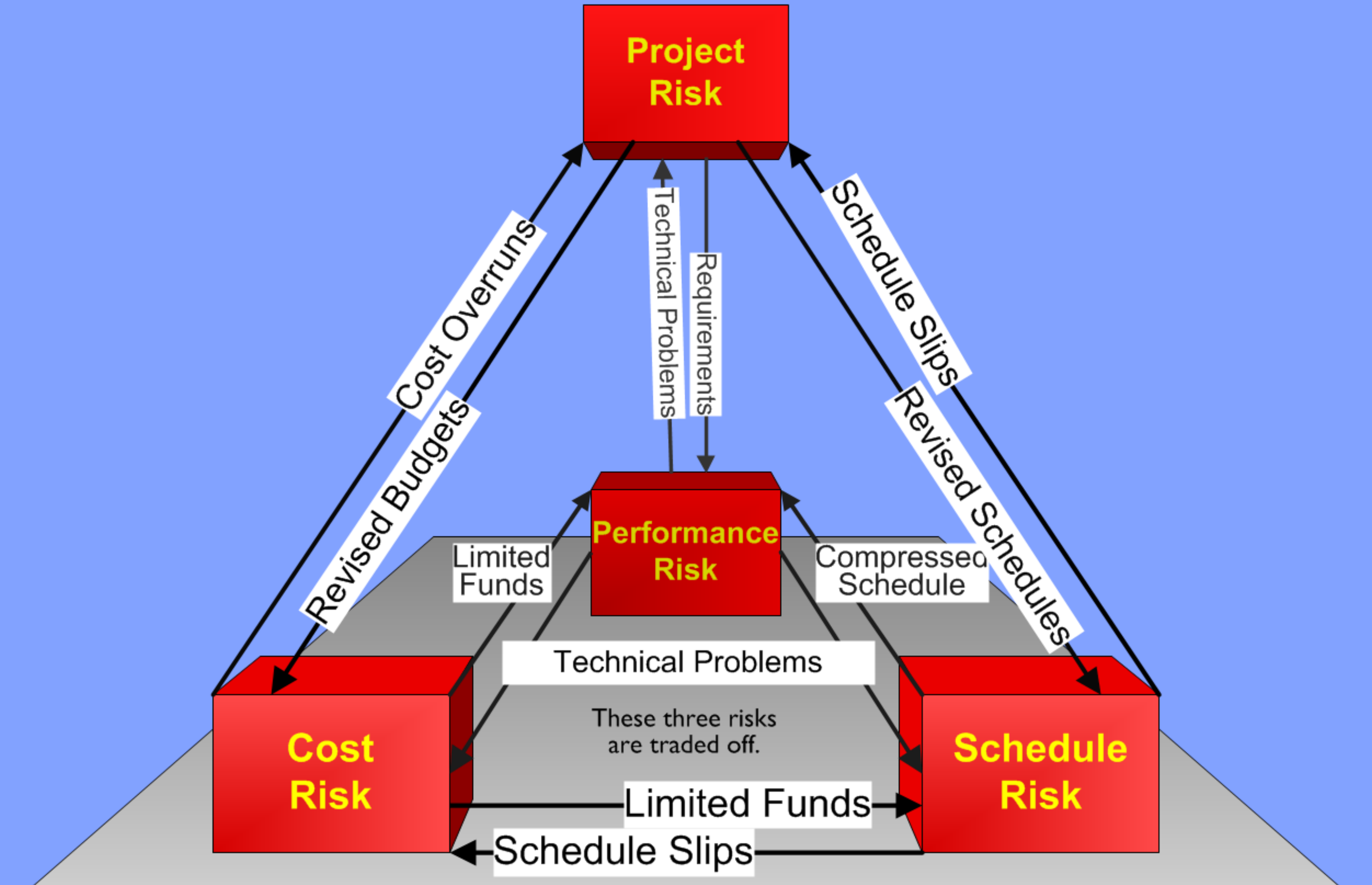
Incipient risk assessment

Early in the design process the design engineer should identify the subsystems that are most likely to cause problems downstream. These might be the most risky, the most complex, ones on the cutting edge, the hardest to test, etc.

The Systems Engineering Process should ensure that a major deliverable at the System Requirements Review is this incipient risk assessment.

Your risk assessment should provide an exhaustive coverage of the problem domain

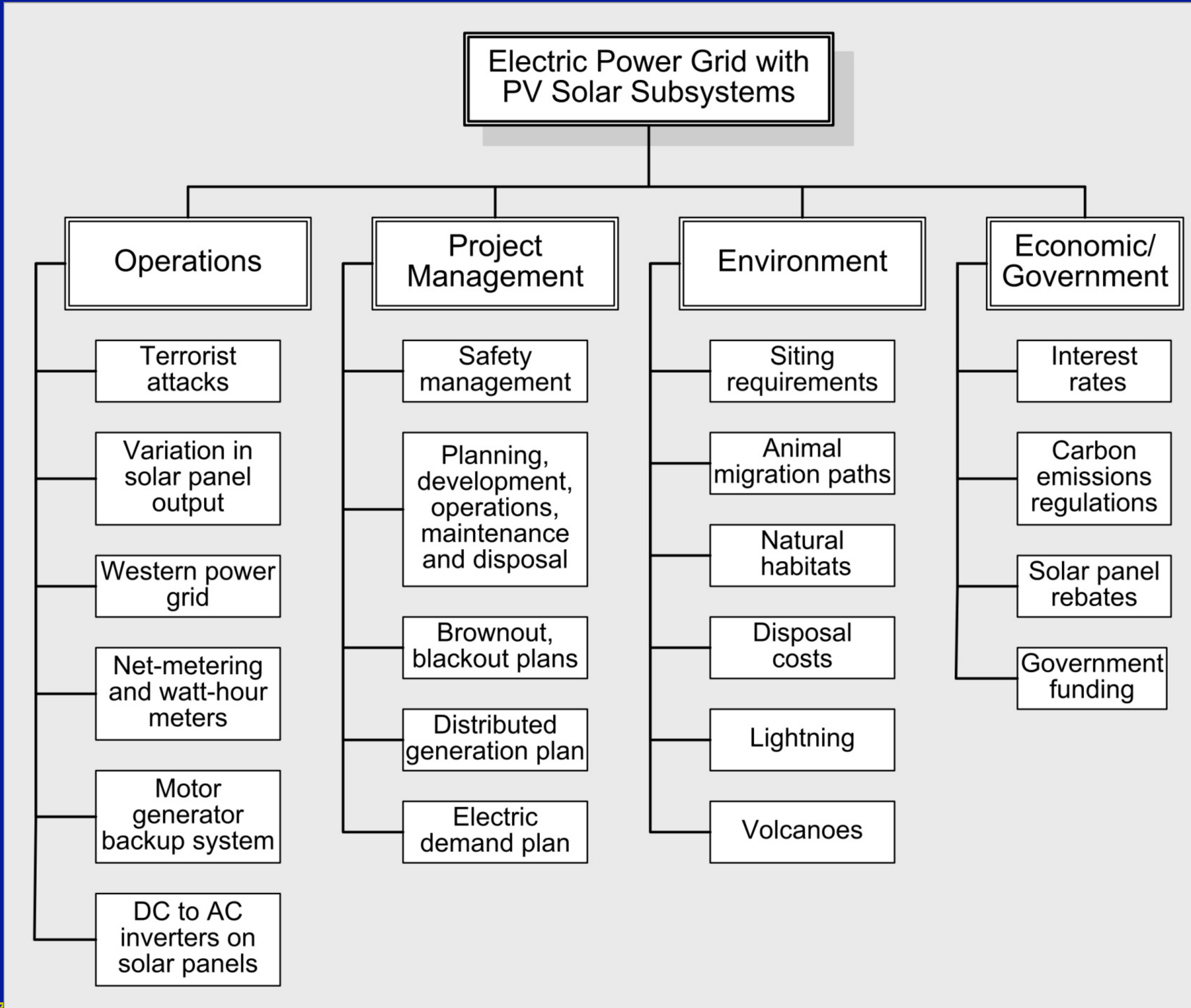
- System risk
  - Performance, schedule and cost of the product
- Project risk



The effect of a risk in one category may become the source of risk in another category.
The most serious of the low-level performance, schedule and cost risks will be elevated to become project risks.

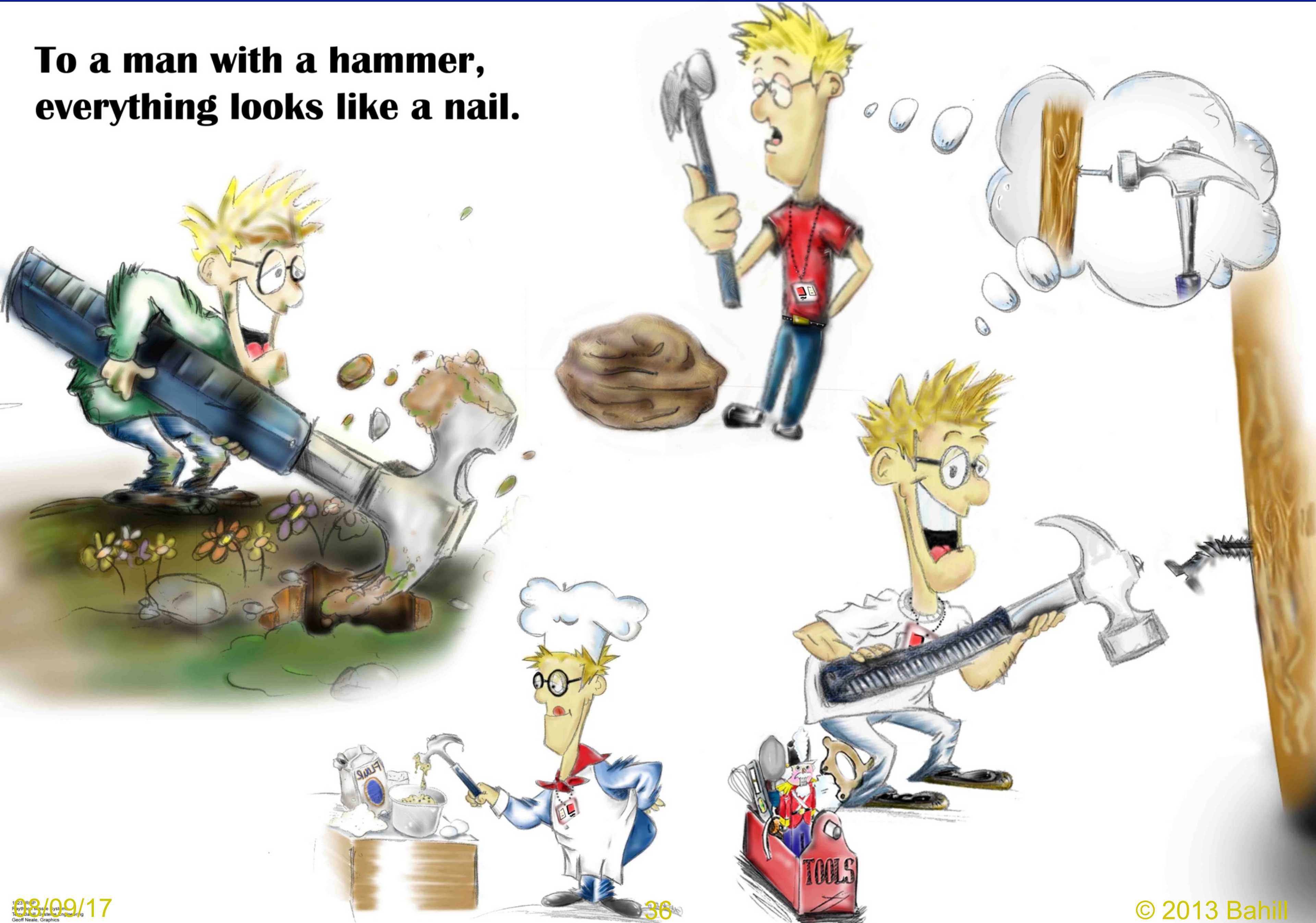
Your risk assessment should provide an exhaustive coverage of the problem domain

Study a hierarchy of models


Electric Power Grid with PV Solar Subsystems
Operations
Terrorist attacks
Variation in solar panel output
Western power grid
Net-metering and watt-hour meters
Motor generator backup system
DC to AC inverters on solar panels
Project Management
Safety management
Planning, development, operations, maintenance and disposal
Brownout, blackout plans
Distributed generation plan
Electric demand plan
Environment
Siting requirements
Animal migration paths
Natural habitats
Disposal costs
Lightning
Volcanoes
Economic/ Government
Interest rates
Carbon emissions regulations
Solar panel rebates
Government funding

People should view different objects differently

To a man with a hammer, everything looks like a nail.



Your risk assessment should provide an exhaustive coverage of the problem domain

Look at many viewpoints

Viewpoints

It is very important to identify the viewpoint for each risk.

We will assess the risk of incorporating solar PV systems into an existing commercial electric grid *from the point of view* of the electric company.

We could have used the point of view of the customer, or the shareholders, or the environment, etc.

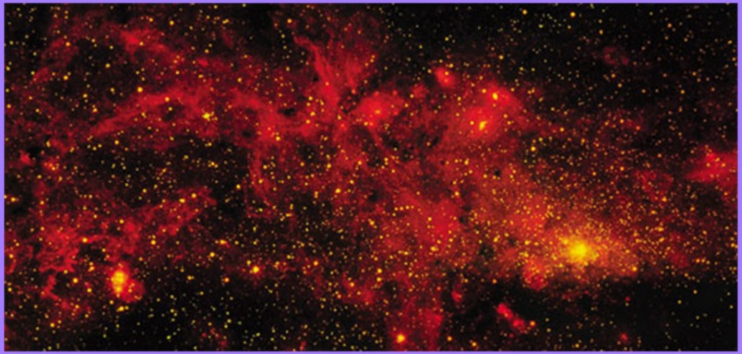
Views and viewpoints are formal architectural entities.

Views

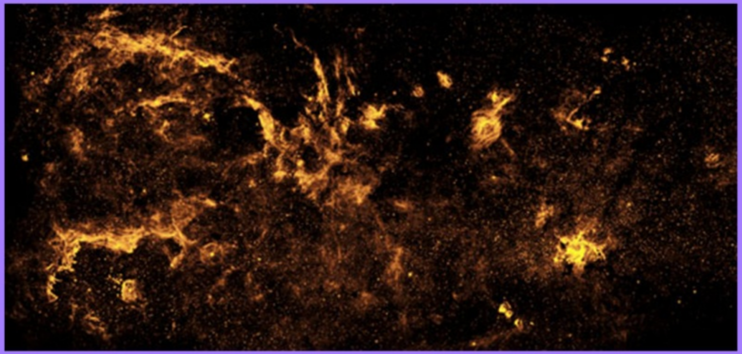
- An architectural description is organized into multiple views
- A view describes the entire system from the perspective of a particular stakeholder.
- A view conforms (a SysML relationship) to a single viewpoint
- A viewpoint
  - identifies stakeholders
  - describes their architectural concerns
  - specifies the modeling language (e. g. SysML)
  - prescribes the modeling method
    (e. g. x dot = Ax +Bu)
  - suggests risks

Four views of the Milky Way galaxy

Hubble's View
1990, visible light (380 to 740 nm) and near infrared (750 to 1400 nm)



Chandra's View
1999, X-rays, 0.2 to 6 nm



Spitzer's View
2003, infrared, 24,000, 70,000 and 160,000 nm

The Center of the Milky Way

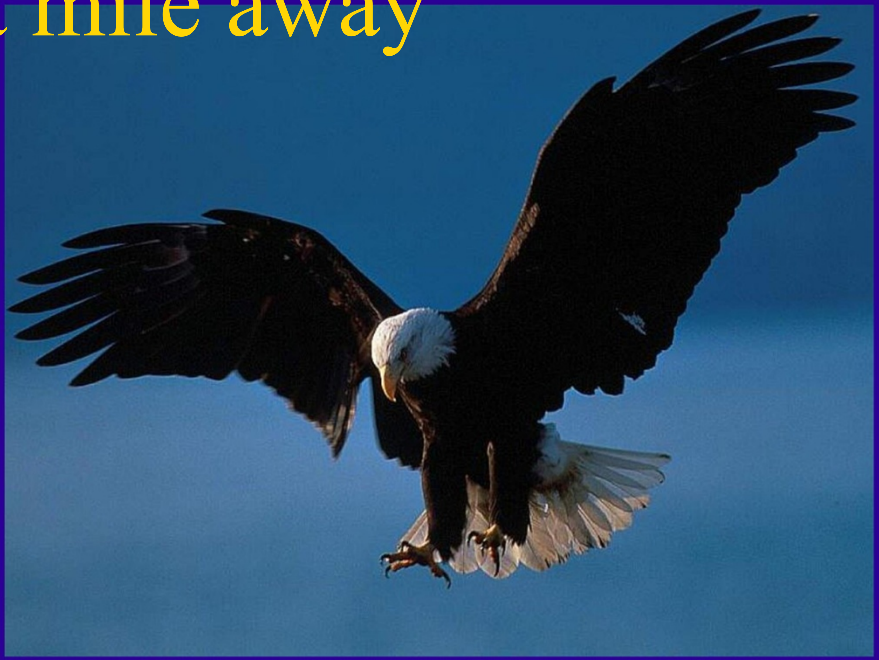
Assume that you are God and you have been asked to design a mouse. Create a half-dozen views of this mouse.

I want a real mouse, not a computer mouse

A baby mouse feels, smells and tastes its mother

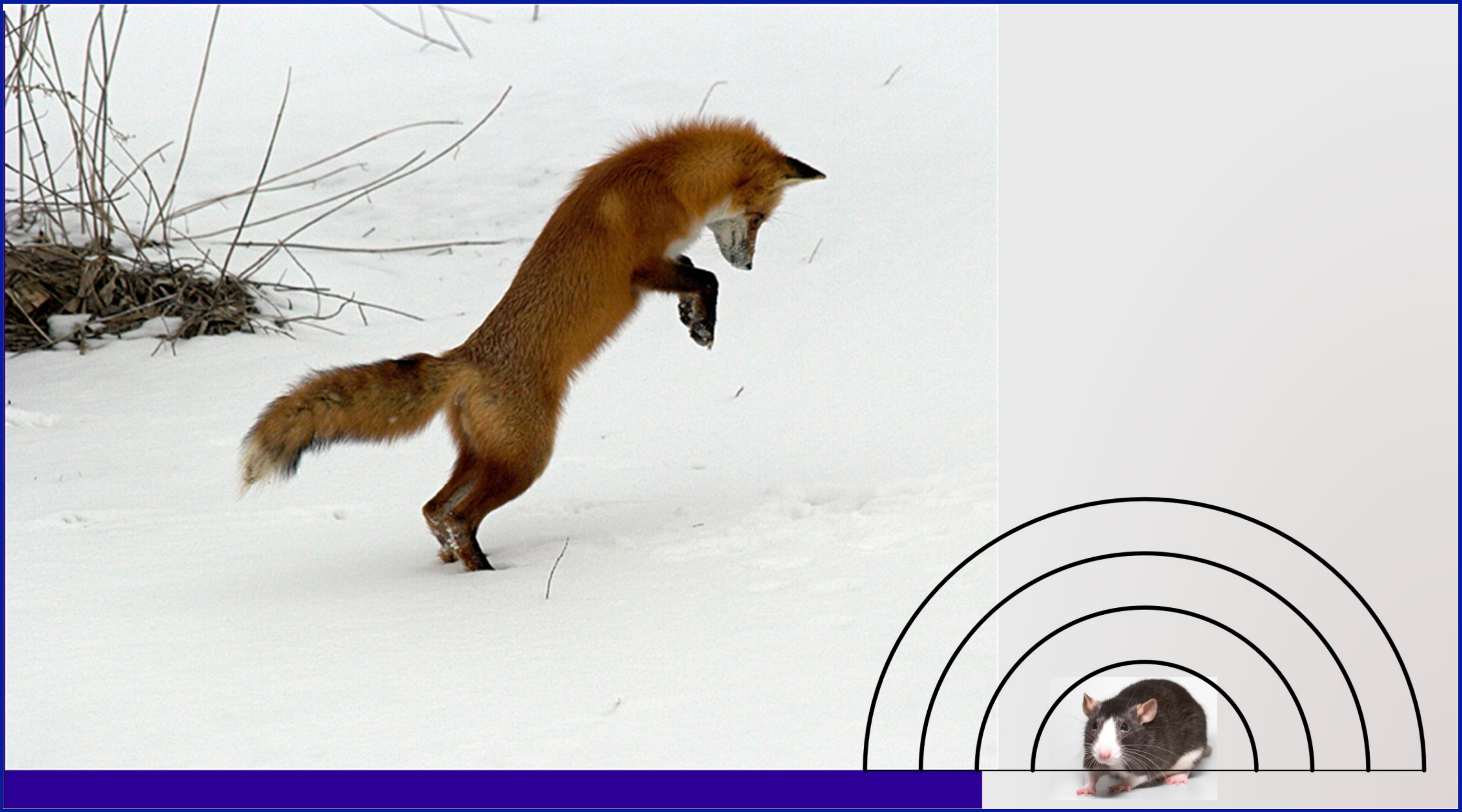
People see a mouse

A hawk or an eagle can see a mouse from a quarter of a mile away



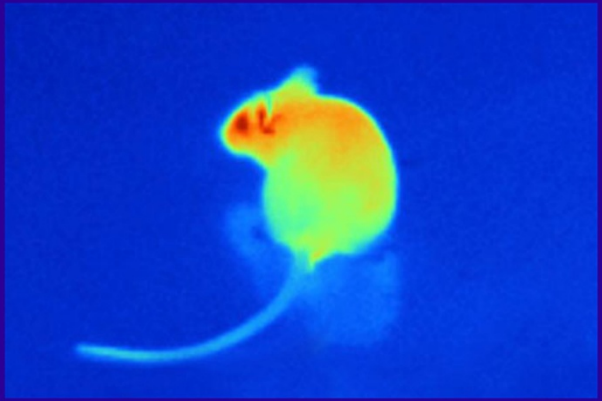
An owl hears a mouse and sees it, even in the dark

A red fox hears a mouse, even under the snow



A dog hears and smells a mouse

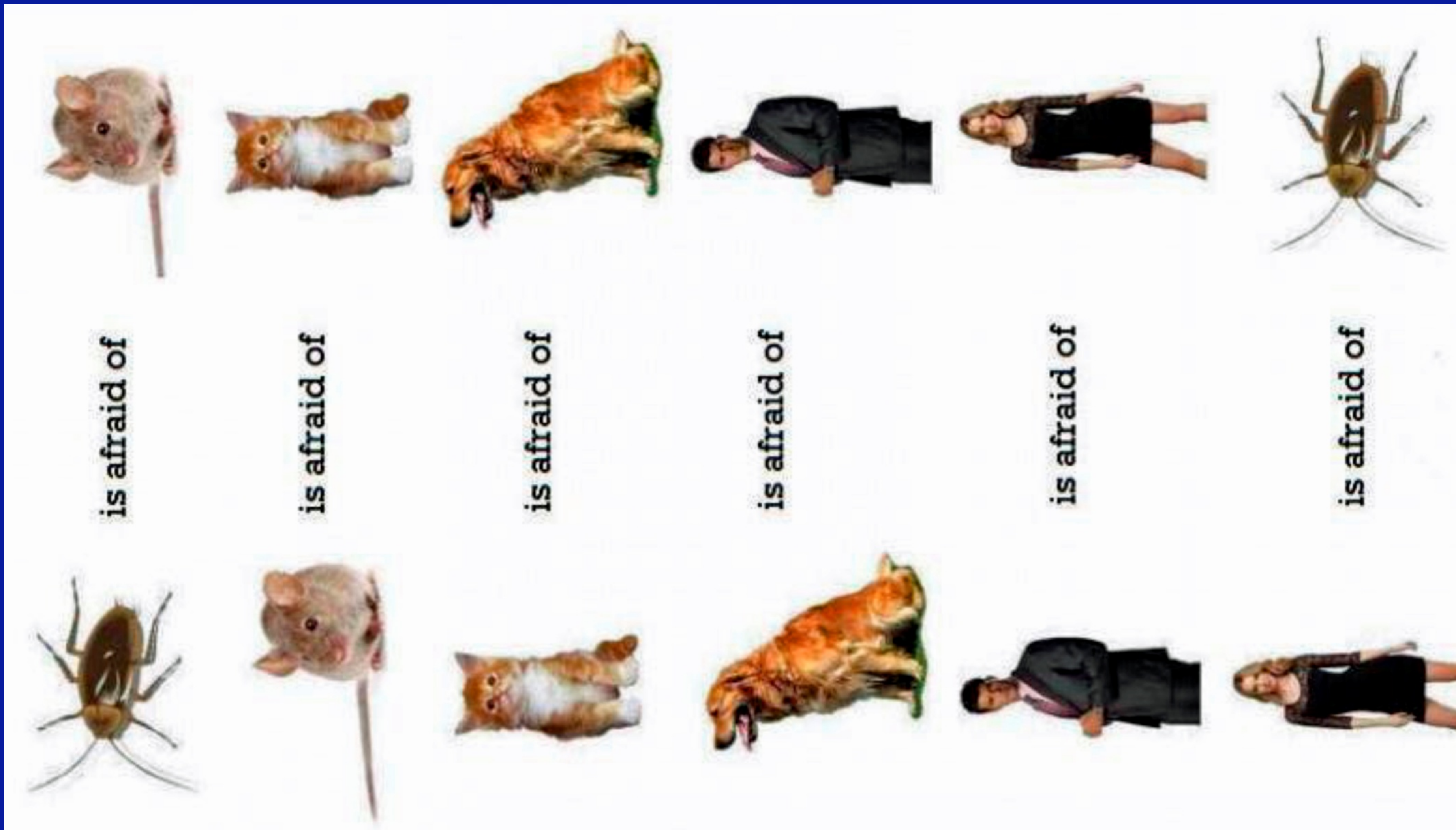
A sidewinder perceives a mouse with its infrared sensors



Sidewinder's viewpoint of a mouse

- Stakeholder: the sidewinder
- Concerns:
  - the mouse shall be warm blooded
  - the mouse shall be neither avian nor aquatic, because the sidewinder does not fly or swim well
  - the mouse shall have a maximum diameter of two inches, so that the sidewinder can swallow it whole
  - the mouse shall provide enough protein to make the hunt worth while
- Modeling language: electro-magnetic radiation, sound, olfaction, vibration, physics, physiology
- Modeling method: neural networks
- Risks: the mouse could bite or scratch the snake, the mouse could get caught in the throat of the snake

The circle of life



State the unknowns

- "The things that come back to haunt you are the things you pretended to understand early on, but didn't."
- "The people who work with me get more points for not knowing something, and knowing that they don't know it, than they do for knowing something."
- "If you've been pretending that you know something you don't, then you won't be able to take advantage of the true information when it becomes known."
- From McCarthy (1995), Microsoft's Visual C++ project manager.

Monty Python said,

"Nobody expects the Spanish Inquisition."

Your risk assessment should provide an exhaustive coverage

- Scrutinize system risk
  - Performance, schedule and cost
- Investigate project risk
- Examine business risk
  - Financial and resource risks to the enterprise*
- Explore safety, environmental and risks to the public
- Study a hierarchy of models
- Look at many viewpoints
- Search throughout the total system life cycle
- Seek unintended consequences to other systems
- Admit what is unknown

3×10^{-6}

Multiple consequences

Failure Event	Consequences	Frequency of occurrence (events per year)
Lightning strikes, the number of lightning strikes per year in Arizona = 10^6	Electrical devices are destroyed, frequency per lightning strike = 10^{-3}	1,000
	A house burns down, frequency per strike= 10^{-4}	100
	A person is injured, frequency per strike=10^{-5}	3
	A person dies, frequency per strike= 10^{-6}	1

Equal ranges

The range of magnitudes for relative likelihood and severity of consequences *must* be the same.

Equal ranges$_2$

Example 1				Example 2			
Likelihood	Severity	Risk	Rank Order	Likelihood	Severity	Risk	Rank Order
10^{-1}	1	1×10^{-1}	1	10^{-1}	6	6×10^{-1}	1
10^{-2}	2	2×10^{-2}	2	10^{-2}	5	5×10^{-2}	2
10^{-3}	3	3×10^{-3}	3	10^{-3}	4	4×10^{-3}	3
10^{-4}	4	4×10^{-4}	4	10^{-4}	3	3×10^{-4}	4
10^{-5}	5	5×10^{-5}	5	10^{-5}	2	2×10^{-5}	5
10^{-6}	6	6×10^{-6}	6	10^{-6}	1	1×10^{-6}	6

It is very important to consider unlikely events, but you may be bucking the tide

This paper was rejected by the journal *Risk Analysis*.

The Associate Editor for Engineering selected a reviewer for this paper.

Her reviewer wrote, “the authors display a total lack of knowledge of electricity grids and many of their statements are plain wrong e.g. section 6.1 ‘The change in power ....brownouts’ - this is completely untrue.”

This is the section he objected to. “…large changes in power output (±60 MW) that would correspond to a solar power output variation of ±3 sigma in a 15-minute period. This change in power output *could* introduce transients onto the grid and *could* produce brownouts.”

The reviewer did not understand that the purpose of a risk analysis to look for unlikely but risky events.

Then Associate Editor agreed with the reviewer and rejected the paper!

And then the Editor in Chief agreed with her!

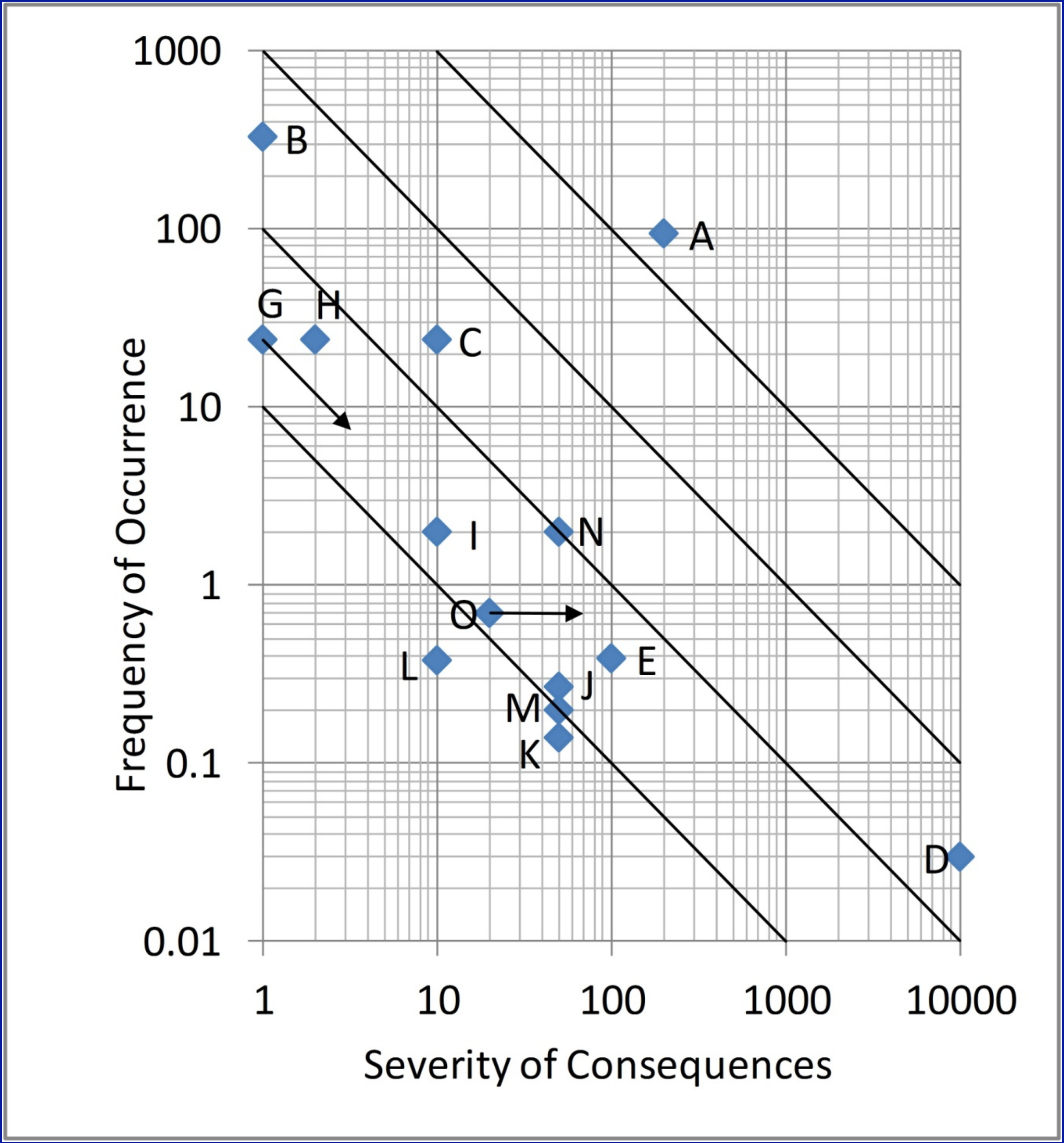
0×∞

This is the handout

The top six* risks are the same as on slide 20, “TEP’s paramount risks.”

Potential Failure Event	Consequences	Frequency of Occurrence in the TEP control area (events per year)	Severity of Consequences	Estimated Risk, defined as frequency times severity	Identification Tag
Physical or cyber terrorist attack on the Western Power Grid	Load shedding, brownouts, blackouts, transportation gridlocks, hardware damage, chaos and cessation of commerce	0	10^6		
Nearby volcanic eruption	Clouds of ash and smoke could cover the sky blocking sunlight to solar panels and reducing solar PV output.	0	10^5		
Solar panel output fluctuates by more than 60 MW in a 15 minute interval due to clouds, thunderstorms, etc.	Power production plummets tripping breakers and leaving customers without electric power. Voltage on the grid could drop and frequency of coal-fired generators could change: transients are harmful to big electric generators.	94.6 This number represents the $\pm 3\sigma$ points for data collected every 15 minutes for an entire year.	200	18,920	A
Feeder circuit disconnects from substation	Feeder circuit voltage gets out of phase with the grid. solar PV	330	1*	330	B
Short to ground on the distribution grid	Equipment is damaged, particularly transformers and capacitor banks.	24	10	240	C
Western Power Grid fails (due to other than terrorist activities)	The western United States would be without electric power.	0.03	10^4	300	D
Lightning strikes the system	Components may be damaged and electric generating capacity would be reduced.	0.39	100	39	E
Grid voltage exceeds ±5% limits	Customer service deteriorates. solar PV systems trip off-line.	24*	1*	24	G
Transient local outages	Outages on transmission or distribution lines trigger shutdown of PV systems.	24	1	24	H
Solar panels accumulate layers of dust or other particles	Efficiency of the solar panels will decrease and energy output will be lower than expected.	2	10	20	I
Junction box fails	Loss of generated power output	0.27	50	14	J
Data acquisition system fails	Data cannot be read from the solar farm, loss of monitoring	0.14	50	7	K
PV module fails	Loss of production capacity	0.38	10	3.8	L
Grid frequency goes out of ±0.5 Hz limits	Small PV systems and big generators trip off-line, perhaps overloading transmission lines. TEP might be fined.	0.2	50*	10	M
Software failure	Software failures are ubiquitous and insidious. They can cause a myriad of problems.	2	50	100	N
Electric storage system fails	Stored energy is lost. Infrastructure might be damaged. This failure event will become more severe as more batteries are used to smooth the load.	0.7	20*	1.4	O

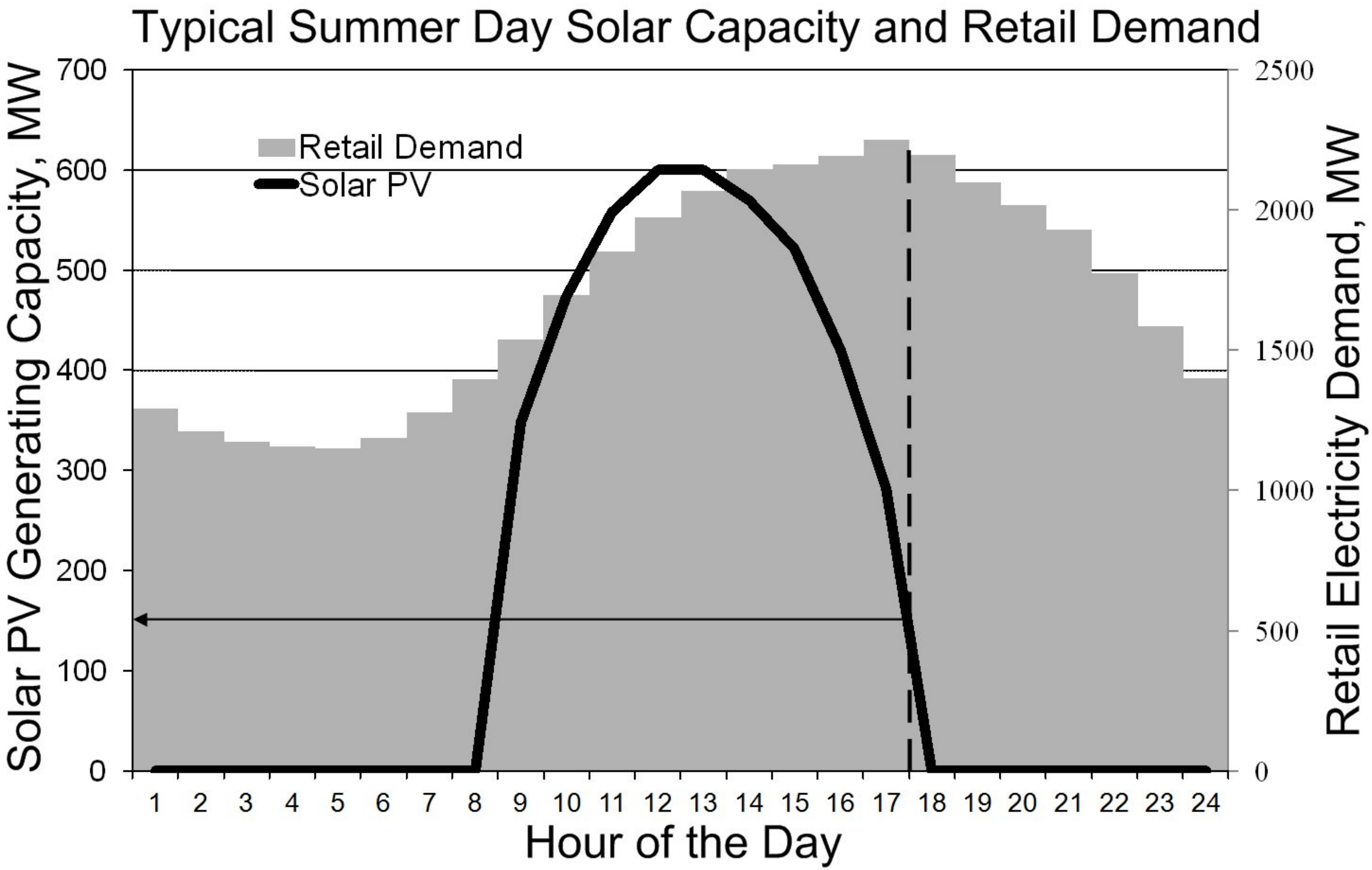
*These values will increase with an increasing number of solar PV subsystems.
Tables IV to XI, estimates are represented with integers or decimals with only one significant figure: Decimal numbers with two or more significant figures were calculated from TEP databases.


1000
100
10
1
0.1
0.01
Frequency of Occurrence
1
10
100
1000
10000
Severity of Consequences
A
B
C
D
E
G
H
I
J
K
L
M
N
O

10^5

	A	B	C	D	E	F	G	H	I	J
Row	Potential Failure Event	Consequences	Frequency of Occurrence, (events per year)	Severity of Consequences, range of 1 to 10^6	Estimated Risk	Risk Rank Order	Identification Tag	Severity, range of 1 to 10	Estimated Risk	Risk Rank Order
4				Log-log technique				Linear technique		
5	Terrorist Attack	Blackouts, chaos	0.01			2		10	0.10	11
6	Volcanic Eruption	Ash blocks sunlight	0.01			3		9	0.09	12
7	Solar power drops 60 MW in 15 minutes	Power production plummets	94.6	200	18,920	1	A	6	568	2
8	Feeder circuit disconnects from substation	Voltage gets out of phase with grid	330	1	330	4	B	3	990	1
9	Short to ground	Equipment is damaged	24	10	240	6	C	5	120	3
10	Western Power Grid fails	Western United States is without electric power	0.03		300	5	D	8	0.2	10
11	Lightning strikes system	Equipment is damaged	0.39	100	39	7	E	5	2.0	7
12	Grid voltage exceeds limits	Service suffers. PV systems trip off-line.	24	1	24	8	G	3	72	4
13	Transient local outages	PV systems shutdown	24	1	24	9	H	3	72	5
14	Dust accumulation	Generated power drops	2	10	20	10	I	5	10	6
15	Junction box fails	Generated power drops	0.27	50	14	11	J	4	1.1	8
16	Data acquisition system fails	Data cannot be read from the solar farm	0.14	50	7	12	K	4	0.6	9

Asynchronous power peaks



Risks that have already been addressed

Failure event Event	Consequences	Solution	Problem Solver
Asynchronous power peaks	Power would not be available when it was most needed	Power reserve planning	TEP
Homeowners Associations (HOAs) could prohibit or penalize PV systems	Homeowners would not buy, install and operate PV systems.	Arizona state law made it illegal for HOAs to impose rules against PV systems.	State of Arizona
Accidents or deaths due to installation of PV systems by homeowners	Homeowners could be electrocuted while installing the systems themselves. Mistakes could kill or injure people.	To qualify for TEP's rebate, the systems must be installed by a *certified* professional.	TEP green incentives program
Electric companies refuse to buy electricity from homeowners	Homeowners would not be able to sell excess power when their output was higher than their consumption	Federal rules require electric companies to buy electricity from their consumers	Federal and State Government
The panels contain toxic chemicals or heavy metals.	Breaking PV panels could release toxic gases or create short circuits.	No toxic chemicals or heavy metals are contained in commercial PV panels	Manufacturers

Photovoltaic solar panels, price decrease$_1$

What if new technology dramatically drove down the cost of solar panels?

This would increase the number of customers who install solar panels.

TEP would have to increase their backup capacity in order to handle customer peak load demands during the period around 5 PM in spite of total cloud coverage.

During the day, these customers would buy less electric energy from TEP and on sunny days, TEP would be required to buy the surplus electricity produced by these customers.

Process: fishbone diagram

Photovoltaic solar panels, price decrease$_2$

This would affect TEP's bottom line: they would lose revenue.

Two things could then happen

TEP could lose money from decreased revenues and increased net-metering costs or

TEP could substantially reduce net-metering payments and rebates.

This would eliminate incentives for residential customers to acquire photovoltaic solar panel systems. This is an unintended negative feedback loop! nUiCs, Destabilizing the solar panel economy.

Photovoltaic solar panels, clouds block sun

Let us speculate that sporadically TEP cannot meet customer demands.

An explanatory theory could be that variations in sunlight intensity could be changing the amount of electricity that was being delivered by photovoltaic solar panels.

We could collect sun intensity data for a typical 24 hour day and also for yearly variations.

These could be compared to TEP's typical load demands.

These data could confirm that variations in sun intensity would make electric power regulation difficult.

The root cause of the difficulty would be clouds covering the sun! risk, Sudden drop in generated electricity.

Process: Juran's cause and effect analysis

Photovoltaic solar panels

What would be the effects of incorporating photovoltaic solar panels into an existing commercial electric power grid?

Unintended consequence

Photovoltaic solar panels

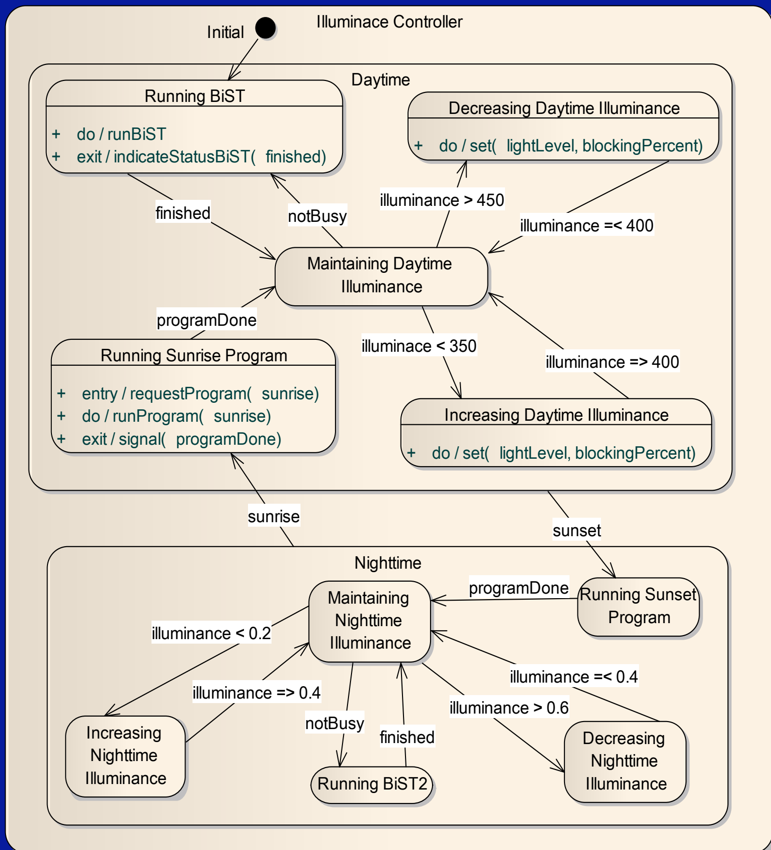
- transform sunlight into electricity
- reflect sunlight back into the atmosphere

Therefore, photovoltaic solar panels prevent sunlight from hitting the Earth.

This reduces the amount of energy absorbed by the Earth and therefore contributes to *global cooling*!

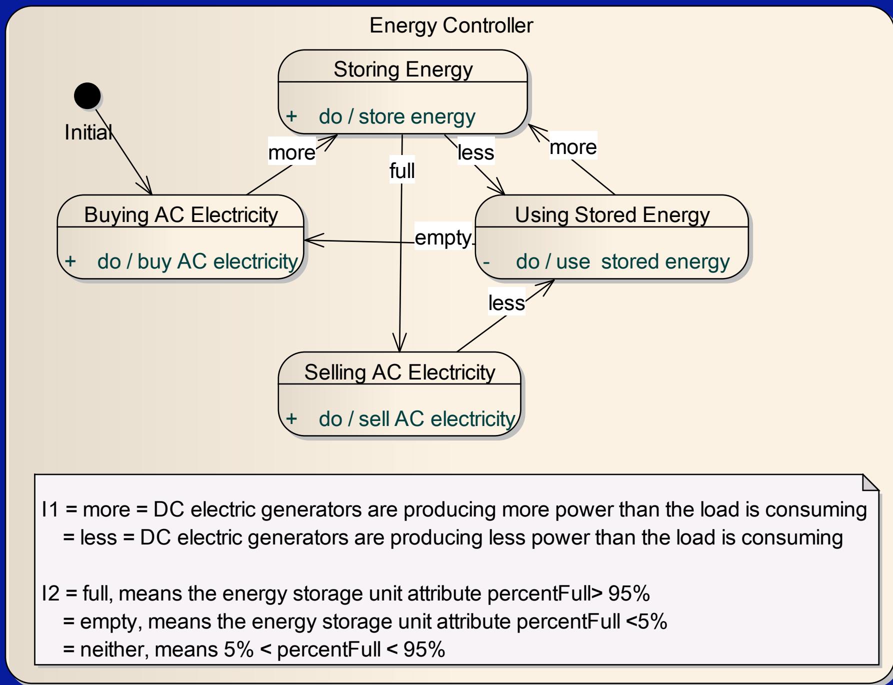
Process: what-if analysis

Control illuminance state machine diagram



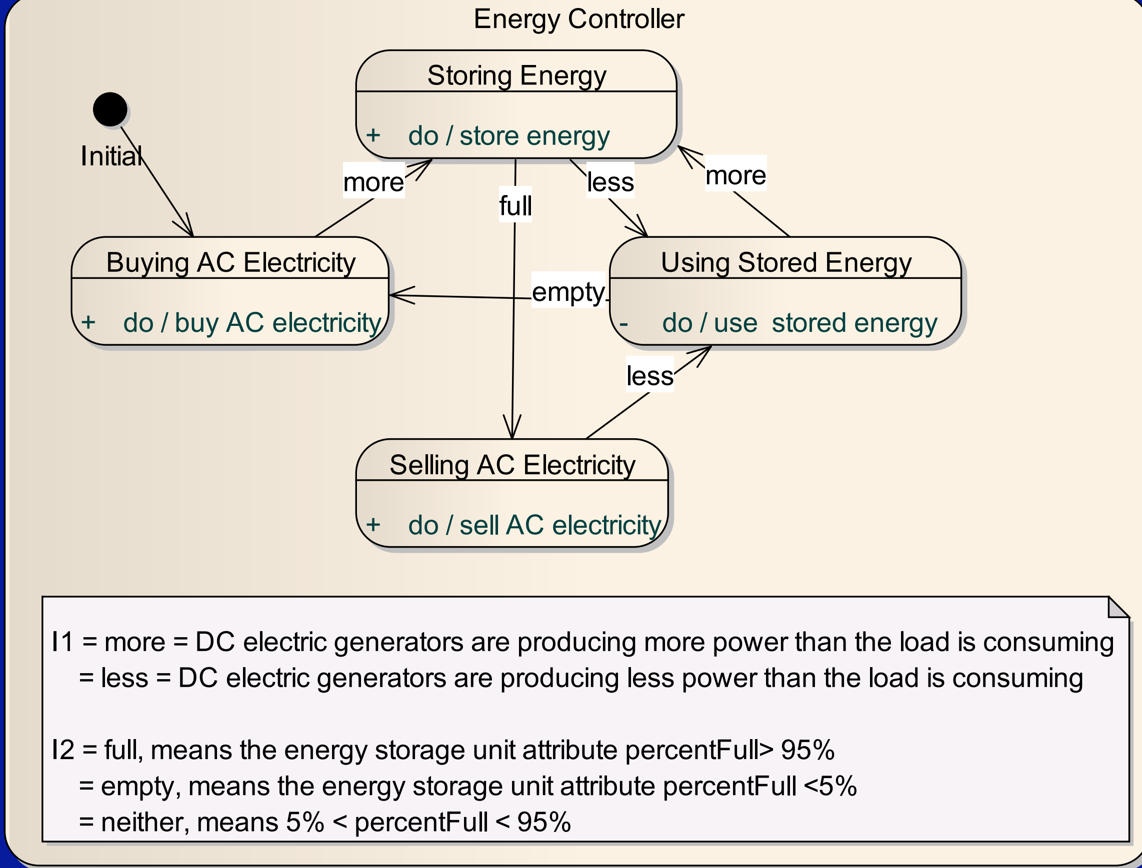
The effects of high altitude on human physiology are well known and they have been managed effectively for decades on Mauna Kea. However, humans are not used to living in a precisely controlled illuminance environment . Studies of the Polaris ballistic missile fleet sailors should be reviewed to see if a regulated environment would cause undesirable entrainment of human circadian rhythms! risk, Controlled illuminance harms humans.

Sell electricity state machine diagram



What if BIMS is in the state of Storing Energy when input-port 1 signals *less* and simultaneously input-port 2 signals *full*? Similarly, What if BIMS is in the state of Using Stored Energy when input-port 1 signals *more* and simultaneously input-port 2 signals *empty*? Actually, this is a small problem, because the logic can be designed to prevent transitions to unwanted states! risk, Hazards and races.

BIMS



This problem can be modeled with the following Boolean equations

- Buy = less And empty
- Sell = Not less And full
- Use = less And Not empty
- Store = Not less And Not full

Therefore this is not a dynamic problem, so it does not need a dynamic (state machine) solution. Replacing it with Boolean equations would also remove hazards and races.

design defect.

We tolerate risk to get rewards

Dénouement

Heisenberg: We cannot simultaneously measure position and velocity with high precision.

Einstein: "So far as the theorems of mathematics are about reality, they are not certain: so far are they are certain, they are not about reality."

Haimes: "To the extent that risk assessment is precise, it is not real. To the extent that risk assessment is real, it is not precise."

Our next lecture will be

Take home message

Uncle Sam wants you to
discover the risks in your system

The BICS BrainTrust

If you are interested, we offer a one week short course on implementing this process in your organization.

Terry Bahill, Fellow of the Institute of Electrical and Electronics Engineers (IEEE), of Raytheon Missile Systems, of the International Council on Systems Engineering (INCOSE) and of the American Association for the Advancement of Science (AAAS).

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Confirmation bias$_1$

- Humans
- notice, pay attention to, listen to, hear, accentuate, note, focus on
- information that
- confirms, affirms, supports, reinforces
- their existing
- beliefs, preconceived notions, attitudes, hypotheses, ideas
- while they
- ignore, filter out, reject, attenuate, neglect
- information that
- challenges, opposes, contradicts,
- their existing
- beliefs, preconceived notions, attitudes, or hypotheses

Confirmation bias$_2$

- This is why people who think that they have perfect memory and recall,
  - make note of instances when they (but not others) correctly recalled events and facts
  - while they ignore instances when they forgot something.

Confirmation bias$_3$

- Senior citizens often believe that they are good drivers despite instances that show that they have poor vision and slow reflexes.
- 30 years ago smokers were in denial.
- Why do so many people believe that rain makes their arthritis symptoms worse?
- Lunar myths. If a person believes that during a full moon there is an increase in accidents (or suicides, or madness, or emergency room admissions), then that person will notice when accidents occur during a full moon, but will be inattentive to the moon when accidents occur at other times.

Confirmation bias

Confirmation bias means that a person notices and looks for information that confirms his/her existing beliefs while ignoring or undervaluing information that challenges his/her preconceived notions.

During WWII the Japanese were certain that their Purple and JN-25 codes were unbreakable, despite evidence to the contrary.

