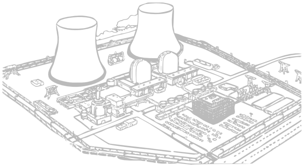


Black swans, or the limits of statistical modelling

Eric Marsden

<eric.marsden@risk-engineering.org>

Do I follow indicators that could tell me when my models may be wrong?

A turkey is fed for 1000 days.

Each passing day confirms to its statistics department that the human race cares about its welfare “with increased statistical significance”.

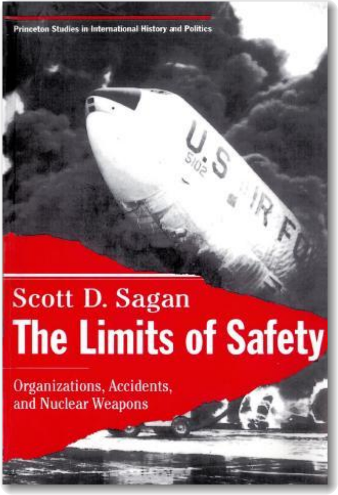
A turkey is fed for 1000 days.

Each passing day confirms to its statistics department that the human race cares about its welfare "with increased statistical significance".

On the 1001st day, a little before Thanksgiving, the turkey has a surprise.

> *Things that have never happened before, happen all the time.*
>
> *— Scott D. Sagan, The Limits of Safety: Organizations, Accidents, And Nuclear Weapons, 1993*

In risk analysis, these are called "unexampled events" or "outliers" or "black swans".



The term “black swan” was used in 16th century discussions of impossibility (all swans known to Europeans at the time were white).

Explorers arriving in Australia discovered a species of swan that is black.

The term is now used to refer to events that occur though they had been thought to be impossible.

Black swans

- Characteristics of a black swan event:
  - an **outlier**
    - lies outside the realm of regular expectations
    - nothing in the past can convincingly point to its possibility
  - carries an **extreme impact**
- Note that:
  - in spite of its outlier status, it is often easy to produce an explanation for the event *after the fact*
  - a black swan event may be a surprise for some, but not for others; it's a subjective, knowledge-dependent notion
  - warnings about the event may have been ignored because of strong personal and organizational resistance to changing beliefs and procedures

Source: *The Black Swan: the Impact of the Highly Improbable*, N. Taleb, 2007


September 2001 terrorist attacks in New York

"That was a risk factor for avian flu that we hadn't really considered before."

– Epidemiologist Tim Uyeki (US CDC), after a man became infected by sucking a rooster's beak to clear its airways, a technique not uncommon in cockfighting circles.

Source: nytimes.com/2004/11/07/magazine/the-flu-hunters.html

Europeans “discovering” America was a black swan event to the native population (of which 80 to 90% died after arrival of Europeans)

Financial collapses

Daily variations of a derivatives portfolio exposed to UK interest rates between 1988 and 2008.

≈ 99% of the variability comes from a single day (collapse of the European Monetary System in 1992).

This one event is critical to the risk level, but it is very difficult to estimate its likelihood with standard statistical/econometric techniques.

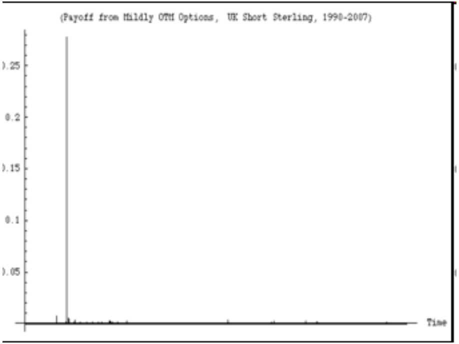


Figure source: *The fourth quadrant: a map of the limits of statistics*, Nassim Nicholas Taleb (2007)

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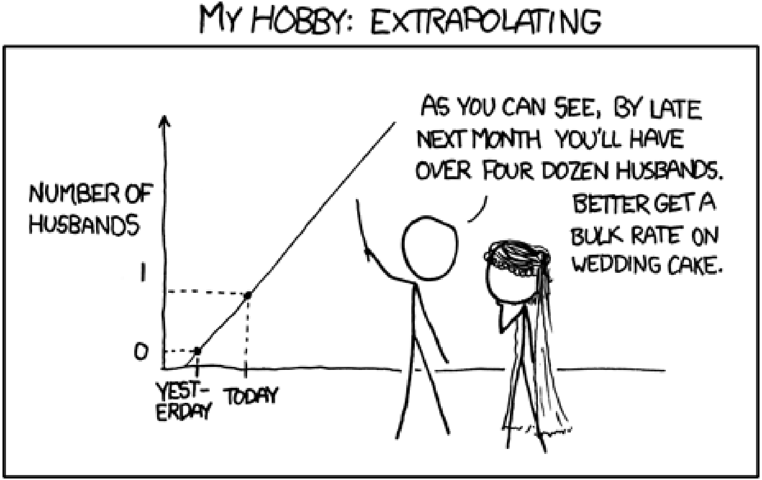
Rare events are not all black swans

- The Fukushima Daiichi tsunami (March 2011, 14 m wave) was caused by a magnitude 9 earthquake
- There were two recorded events of similar magnitude in that area (Sanriku coast):
  - 9th century: earthquake of estimated magnitude 8.6
  - 17th century: earthquake of estimated magnitude 8.1, 20 m tsunami
- These historical records seem not to have been taken into account when designing the Fukushima Daiichi nuclear power plant
  - design basis was a maximum wave height of 5.7 m
- The 2011 tsunami could have been imagined using available historical information
  - not a black swan according to our definition

Risks of extrapolation



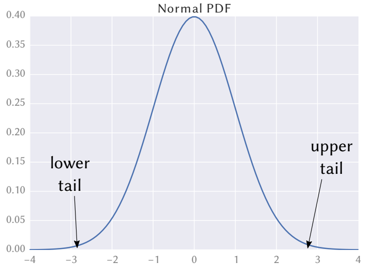
Black swans vs risk analysis

- Some fundamental assumptions in risk management:
  - You can identify hazards in a relatively exhaustive manner
    - the set of possible future events is delimited and known
    - no “unknown unknowns”
  - You can estimate the probability of future events and the magnitude of their consequences
  - If the risk is not acceptable to you, you can act to modify the probabilities or the magnitude of consequences
- Many of these assumptions are invalid when dealing with black swans and situations with high uncertainty

Statistical characteristics of black swans

"Thin-tailed" probability distributions

- The "tail" of a probability distribution is the part which is far away from the mean
- Typical examples of thin-tailed probability distributions:
  - normal (Gaussian) distribution
  - exponential distribution
- For a normal distribution:
  - probability of an observation which is more than 6 standard deviations from the mean (a "six-σ event") is $9.9 \cdot 10^{-10}$
  - a 10-σ event is less frequent than one day in the life of the universe

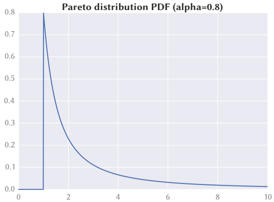


"Fat-tailed" probability distributions

- Extreme events carry significant weight
  - fairly high probability of something "unusual" occurring
- More formally, the tail of the distribution follows a **power law**:

$$\Pr[X > x] \sim x^{-\alpha} \text{ as } x \to \infty, \qquad \alpha > 0$$

where $\sim$ means "is asymptotically similar to".



- Example: the Pareto distribution
  - designed by economist V. Pareto to model distribution of wealth in capitalist societies
  - a good fit for the severity of large losses for worker compensation, the level of damage from forest fires, the energy released by earthquakes…
- Example: the oil shock in 1973 was a 37-sigma event

Two caricatures of probability distributions

Mediocristan

Events are easy to predict.

Exceptions occur, but don't carry large consequences.

Example: distribution of population's weights follows a Gaussian distribution. Add the heaviest person on the planet to a sample of 1000 people, and the total weight will barely change.

"thin tails"

Extremistan

Exceptions can be everything.

Example: distribution of wealth in capitalist economies. Add Bill Gates to your sample of 30 random people and mean wealth will jump by a factor of 100 000.

Winner takes all effects (sales of novels, albums).

Future is hard to predict from past information.

"fat tails"

Source: *The Black Swan: The Impact of the Highly Improbable* by N. Taleb

Winner takes all effects

- Less than 0.25% of all the companies listed in the world represent around half the market capitalization
- Less than 0.2% of books account for approximately half their sales
- The top 1% of bands and solo artists now earn 77% of all revenue from recorded music
- Less than 0.1% of drugs generate a little more than half the pharmaceutical industry's sales
- "The rich get richer"
- Leads more often to "golden goose" events (extreme upside) than to "black swan" events (extreme downside)

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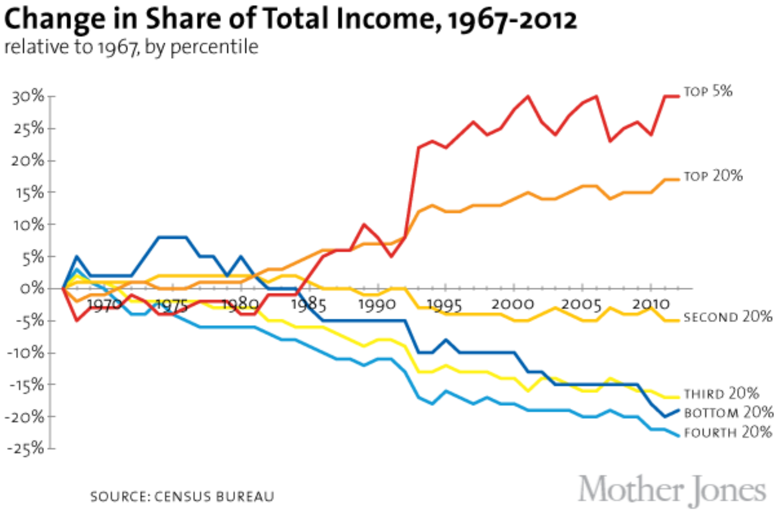
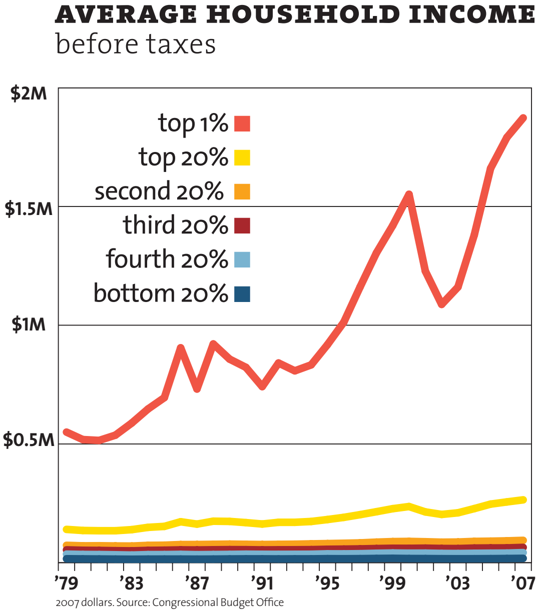
Example: income inequality in USA



Source: motherjones.com/politics/2013/09/charts-income-inequality-middle-class-census



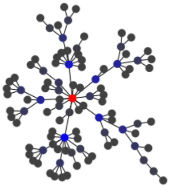
"The rich get richer"

Data for USA, but analysis by economist T. Piketty suggests similar trends for most developed countries.

Greater income inequality means a more fat-tailed income distribution and more outliers in the population.

Source: motherjones.com/politics/2011/02/income-inequality-in-america-chart-graph

Preferential attachment processes



- The Barabási–Albert model is an algorithm for generating random scale-free networks using a preferential attachment mechanism
- Generates a “fat-tailed” distribution following a Pareto distribution or power law in its tail
- Mechanism which might explain:
  - distribution of the sizes of cities
  - wealth of extremely wealthy individuals
  - number of citations received by scientific publications
  - number of links to web pages

Event probability in Mediocristan

Events in Mediocristan:

- In a developed country a newborn female is expected to die at around 79, according to insurance tables
- When she reaches her 79^{th} birthday, her life expectancy, assuming that she is in typical health, is another 10 years
- At the age of 90, she should have another 4.7 years to go
- If you are told that a person is older than 100, you can estimate that he is 102.5 and conditional on the person being older than 140 you can estimate that he is 140 plus a few minutes
- The conditional expectation of additional life drops as a person gets older

Event probability in Extremistan

- Events in Extremistan:
  - the conditional expectation of an increase in a random variable does not drop as the variable gets larger
  - conditional on a loss being worse than 5 units, it will be around 8 units
  - conditional on a move being more than 50 units, it will be around 80 units
  - if we go all the way until the sample is depleted, the average move worse than 100 units is 250 units!
  - there is "no typical" failure and "no typical" success
- Examples:
  - movements on the stock market
  - predictions of drug sales: sales estimates are often very different from actual sales

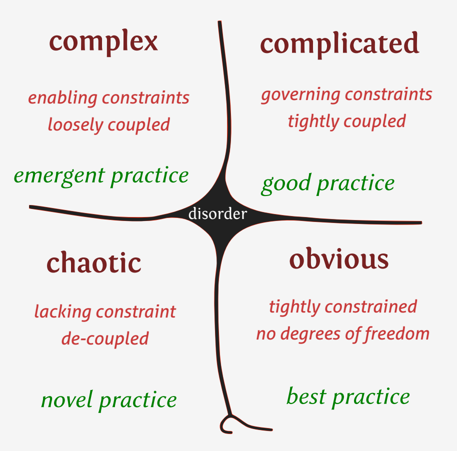
Coping with black swans

Attempting to cope with black swans

- By definition, black swan events are not predictable
- You can try to determine your level of exposure to them
  - is my system simple/complicated/complex/chaotic?
  - what is my level of confidence in our knowledge of the system?
- Coping techniques that try to **reduce their likelihood**:
  - training people to increase their "safety imagination"
  - stress tests
  - horizon scanning exercises: a methodical way of identifying threats and opportunities
- Coping techniques that try to **reduce their impact**:
  - logics of precaution
  - post-normal science and participatory governance
  - increased system resilience

Cynefin framework and complexity

- Describes five system contexts depending on relationship between cause and effect
- Contexts: obvious, complicated, complex, chaotic, disorder
- A "cliff" between obvious and chaotic
- Describes the types of issues that decision-makers face in these contexts



Cynefin framework: adapted from figure by Dave Snowden

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Decision-making & black swans

	simple payoffs	complex payoffs
thin-tailed distributions	Very robust to black swans	Quite robust to black swans
fat-tailed distributions or unknown tails	Quite robust to black swans	Susceptible to black swans (limit of statistics)

humility needed!

Simple payoffs: binary outcomes

Complex payoffs: dependent on expected value, possibly leveraged

Source: N. Taleb

Safety imagination

> *The only surprise is that we're surprised when we're surprised.*
>
> *— Former US Secretary of Defense Donald Rumsfeld*

- Safety imagination: concept proposed by N. Pidgeon to characterize ability to "think outside the box"
  - help develop richer accident scenarios than those normally considered in risk assessments
  - reduce complacency on safety issues
  - can trigger discussion on new approaches to managing risks and emerging hazards
  - conducive to learning

See *Man-made disasters: why technology and organizations (sometimes) fail*, N. Pidgeon & M. O'Leary, Safety Science, 2000, DOI: 10.1016/S0925-7535(00)00004-7

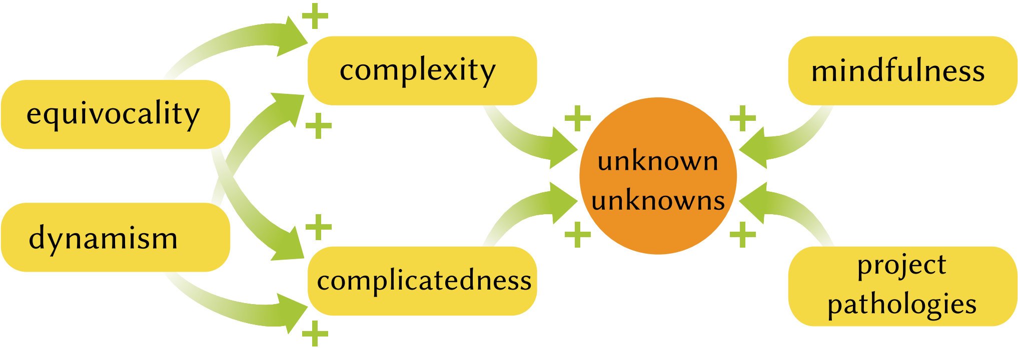
Fostering safety imagination: suggestions

- ▷ Attempt to fear the worst; allow no worst case situation to go unmentioned
- ▷ Use good meeting management techniques to elicit varied viewpoints
- ▷ Play the "what if" game with potential hazards
  - brainstorming to avoid groupthink
- ▷ Suspend assumptions about how the safety task was completed in the past
- ▷ Tolerance of ambiguity will be required when approaching the edge of a safety issue
  - newly emerging safety issues will rarely be clear
- ▷ Force yourself to visualize "near-miss" situations developing into accidents

Source: *Man-made disasters: why technology and organizations (sometimes) fail*, N. Pidgeon & M. O'Leary, Safety Science, 2000, DOI: 10.1016/S0925-7535(00)00004-7

FACTORS CONTRIBUTING TO UNKNOWN UNKNOWNS

The six factors shown here tend to increase the likelihood of unk-unks (surprises) in projects.



Source: *Reducing Unwelcome Surprises in Project Management*, Browning & Ramasesh, Sloan Management Review, 2015

⚠ Social conformity is a strong yet subtle phenomenon

- The **Asch conformity experiments** in psychology (1950s) analyzed to what extent individuals yield to or defy a majority group & effect of such influences on beliefs
- Example experimental setup: a rigged "perceptual" task
  - a group of 8 participants are asked to say aloud, in turn, which line in the right-hand group matched the length of the left-hand line
  - all but one of the participants are working with the experimenter ("confederates")
  - each confederate in turn gives the same incorrect response
  - the subject of the experiment is asked to answer last
- Measures **normative social influence**: willingness to conform publicly to attain social reward and avoid social punishment

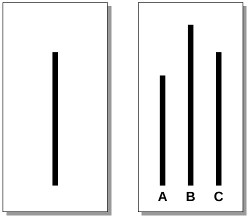


Figure by Fred the Oyster via Wikimedia Commons, GFDL

⚠ Social conformity is a strong yet subtle phenomenon

- Results: complex mixture of individual differences in subject's reaction to the experimental situation
  - some individuals yield to group norm, some express doubt but conform, some resist (most frequent reaction)
- Striking example of people publicly endorsing the group response despite clearly knowing that they were approving an incorrect outcome
  - potentially dangerous feature of group dynamics!
- Related experiments:
  - Milgram (1960s) measured the willingness of people to obey an authority figure who instructed them to perform acts conflicting with their personal conscience (inflicting electric shocks on a "learner")
  - Stanford prison experiment (1970s) assessed willingness of people role-playing as prison guards to abuse their "prisoners"

⚠ Social conformity is a strong yet subtle phenomenon

- Famous experiment on the "**bystander effect**" or "**diffusion of responsibility**"
  - people defer to others on how to interpret ambiguous situations
  - don't like overreacting to later appear ridiculous
  - if you observe other people doing nothing in response to an apparent risk, you're more likely also not to respond
- Experiment: observe how people react to a room which progressively fills with smoke
  - first case: subject is along with the experimenter, 75% of them report the smoke
  - second case: subjects sitting in the room with passive people (confederates, told not to react by experimenter), only 10% report the smoke

Source: Latané, B., & Darley, J. M. (1968). *Group inhibition of bystander intervention in emergencies*. Journal of Personality and Social Psychology, 10(3), 215-221

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A “red team”

- A red team is an independent group that provides an **adversarial perspective**, challenging an organization to improve its effectiveness
  - imagines attacks from a competitor, worst-case futures, and nightmare scenarios
  - challenges assumptions and examines how well current plans would work
- Goal:
  - to think through consequences of the bad event
  - to consider what measures might be possible now to improve ability to deal with the results
  - not to precisely predict the threats or to plan in detail
- Concept developed by the military
- Extension of the “devil’s advocate” concept in group discussions

Scenario analysis

- ▷ Scenario analysis follows a systematic process to create a set of **plausible** and vividly **contrasting narratives** that describe possible **evolutions of key areas of uncertainty**
- ▷ These narratives (scenarios) examine the social, political, economic, and technological forces that might affect a project or strategy
- ▷ They are developed by a **diverse team** including decision-makers, experts and stakeholder representatives
- ▷ Can be used to illuminate "**wild cards**" (high impact, low probability events that happen so fast that social systems cannot effectively respond)
  - example: possibility of the earth being struck by a meteor
- ▷ A method for developing *foresight* (thinking about possible futures) which feeds in to strategy development

TRIZ: theory of solving problems creatively

- The TRIZ method (theory of resolving invention-related tasks) was developed by Russian inventors
- Steps in a “reverse TRIZ” used for hazard analysis:
  1. Start with the objective
  2. Reverse this objective
  3. Exaggerate/amplify the objective (hazard)
  4. Identify resources needed to reach the objective
- Benefits of this approach:
  - puts participants in a positive mindset about identifying potential hazards (can reduce lack of engagement in the process)
  - encourages people to free their imagination

Source: Critical Uncertainties blog by Matthew Squair

TRIZ: theory of solving problems creatively

Example application of TRIZ to a hazard analysis

- Objective: Minimise the risk of a plant gas leak and explosion
- Reversed: I want to increase the risk of a plant gas leak and explosion
- Amplified: I want lots of gas leaks and when they occur big explosions!
- Resources:
  - Lots of pipework joints
  - Store lots of gas in the system
  - Make sure that gas can leak into areas where it doesn’t disperse
  - Ensure that there’s lots of maintenance…

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Scenario analysis

Diagram of the Scenario Process, as used by World Bank

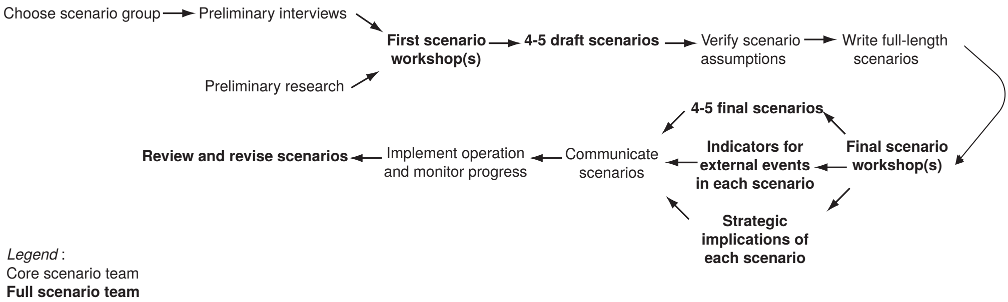


Figure source: *Scenario Analysis: A Tool for Task Managers*, World Bank report

The difficulty of predicting

> *Prediction is very difficult, especially if it's about the future.*

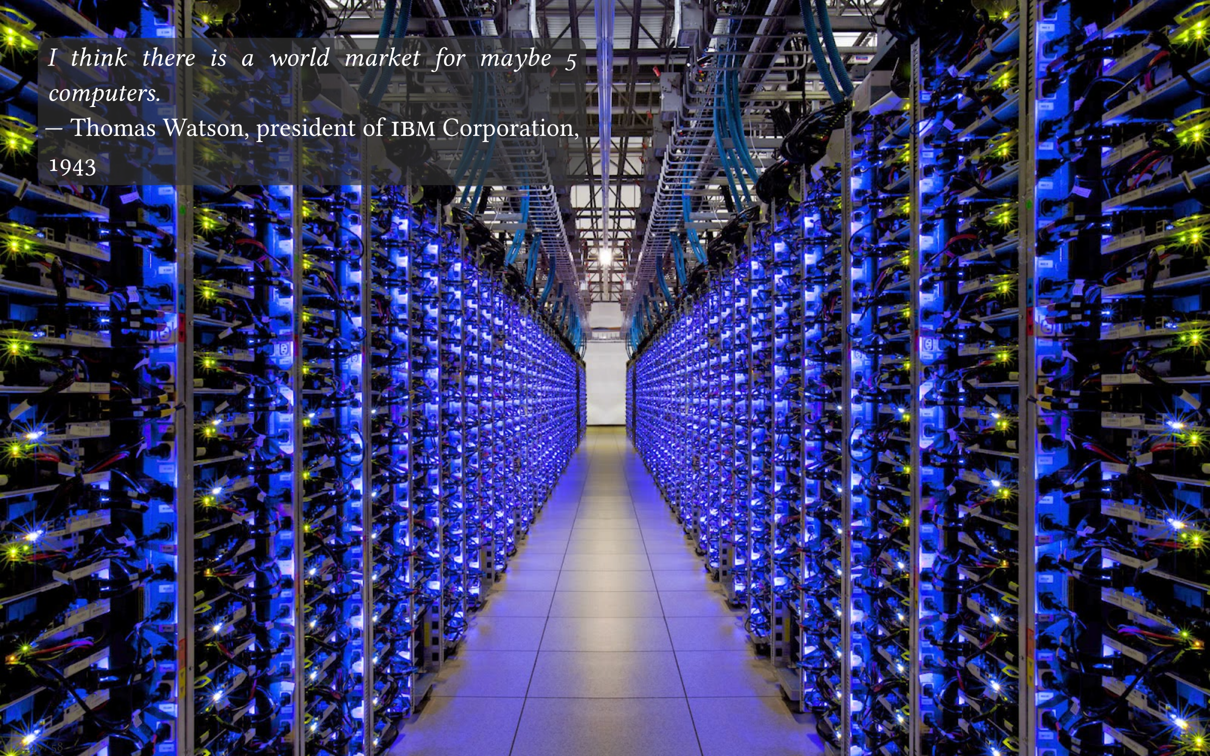
— Nils Bohr (disputed quotation)

> *Prophesy is a good line of business, but it is full of risks.*

— Mark Twain in *Following the Equator*

Heavier than air flying machines are impossible.

— Lord Kelvin, President of the Royal Society, 1895



I think there is a world market for maybe 5 computers.
— Thomas Watson, president of IBM Corporation, 1943

Who the hell wants to hear actors talk?

— H. M. Warner, Warner Bros, 1927

Anticipatory Failure Determination (AFD)

- AFD is an inventive problem solving technique
- Standard failure analysis methods such as FMEA: ask designer to look for a cause of a failure mode
- AFD reverses this approach, asking designers to
  - view failure of interest as the intended consequence
  - try to **imagine ways to ensure that the failure always happens repeatably**
- Can help to overcome the phenomenon of denial ("oh, that wouldn't happen to our product")
- Can increase amount of creativity deployed in analysis of failures

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Anticipatory Failure Determination: steps

1. **Inverse the formulation** of the problem: not "how did it happen?" but identifying steps to produce the problem
   - identify the conditions that lead to the failure
   - identify the scenario or events involved
2. Search for methods to **reproduce the failure**
   - identify all the standard ways of creating the failure
   - for example using function analysis methods
3. Verify that **resources** are available to cause the failures
   - resource categories: substances, field effects, space available, time, object structure, system functions, and other data on the system
   - for each of the potential solutions, identify whether the required resources are available to allow failure

Stress testing

- ▷ Stress test: an analysis or simulation designed to determine the **ability to deal with an exceptional event**
  - tests robustness with respect to catastrophes
  - a complement to standard "best estimate" projections and risk analyses
- ▷ Widely used in finance, with scenarios such as:
  - *"What happens if the unemployment rate rises to X% in a specific year?"*
  - *"What happens if GDP falls by X% in a given year?"*
  - *"What happens if interest rates go up by at least X%?"*
  - *"What happens if oil prices rise by 200%?"*
- ▷ Note: a stress test is only as good as the scenarios on which it is based

Example applications of stress testing

- Used by regulators to ensure that banks and insurance companies have adequate capital levels to resist to extreme — but plausible — events
  - in particular since the 2008 financial crisis
- Regulatory stress testing in the banking sector to ensure capital levels are adequate
  - Comprehensive Capital Analysis and Review (CCAR) in the USA
  - ECB "Comprehensive Assessment" stress tests in the EU
  - avoid possibility of systemic risks in the financial sector (domino effects where failure of one organization leads to a cascade of failures)
- Also used by businesses, insurers and governments to analyze emerging threats and possible vulnerabilities
  - example: University of Cambridge *Center for risk studies* publishes threat scenarios at `cambridgeriskframework.com`

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Aside: video on systemic risks in finance

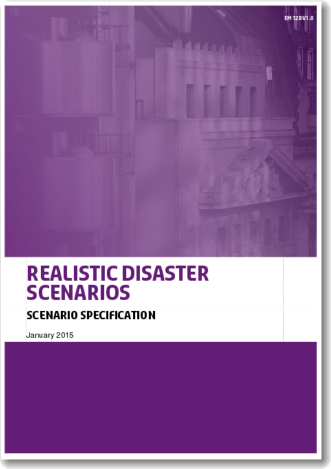
View video online: `youtu.be/UzW195qWHYg`

More information: `systemic-risk-hub.org`

Example applications of stress testing

The insurer Lloyd's maintains a set of mandatory Realistic Disaster Scenarios to stress test both individual syndicates and the market as a whole. The event scenarios are regularly reviewed to ensure they represent material catastrophe risks.

Source: `lloyds.com/the-market/tools-and-resources/research/exposure-management/realistic-disaster-scenarios`



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Post-normal science

- A concept developed by Silvio Funtowicz and Jerome Ravetz for situations where “facts are uncertain, values in dispute, stakes high and decisions urgent”
- When using scientific knowledge for policy-making, some elements should be made explicit:
  - nature of uncertainty present in the analysis (stochastic, epistemic or axiotic/values-based) and an estimate of level of uncertainty
  - the quality (or “pedigree”) of the analysis (are the data and assumptions new or have they had time to mature?)
  - the stakes of the decision (costs and benefits and value commitments of all stakeholders, impacted timeframe)
  - the impact of different value systems and ethics on the possible decisions

Source: *Science for the post-normal age*, S. Funtowicz & J. Ravetz, Futures, 1993

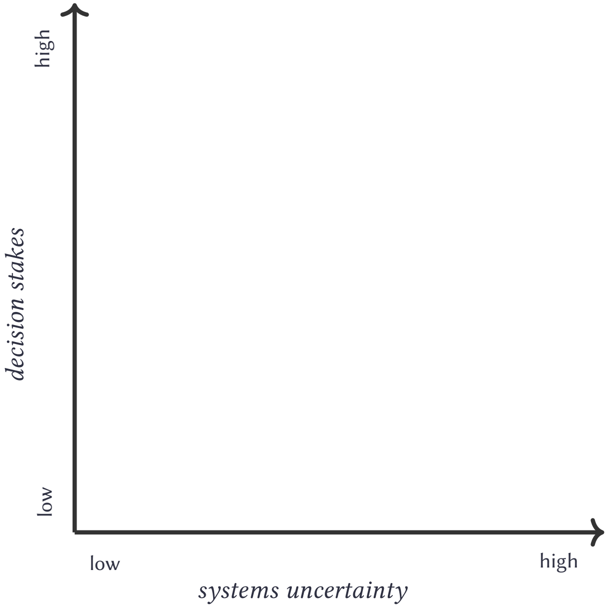
Post-normal science

- Related notion of *trans-science*: questions that can be asked of science, but not answered by it
  - risk problems which cannot be resolved by sound science or evidence-based risk assessment
  - questions of fact which can be stated in the language of science but not answered
  - questions that "transcend" science
- Example: biological effects of exposure to low-level ionizing radiation
  - testing whether genetic response to radiation is linear (including at very low doses) would require experiments on billions of mice
  - not feasible in practice
  - cannot be answered by direct scientific investigation

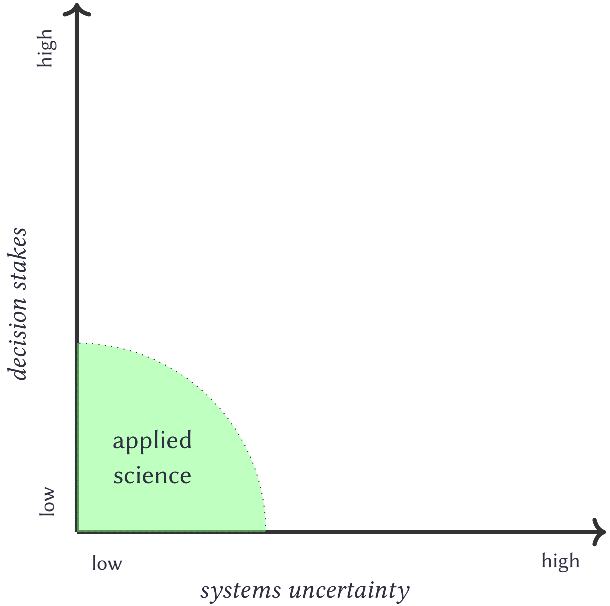
"I would rather have questions that can't be answered than answers that can't be questioned."
-- Richard Feynman

Source: *Science and trans-science*, Alvin Weinberg (1972), Minerva, 10, 1972, 209-222

Post-normal science

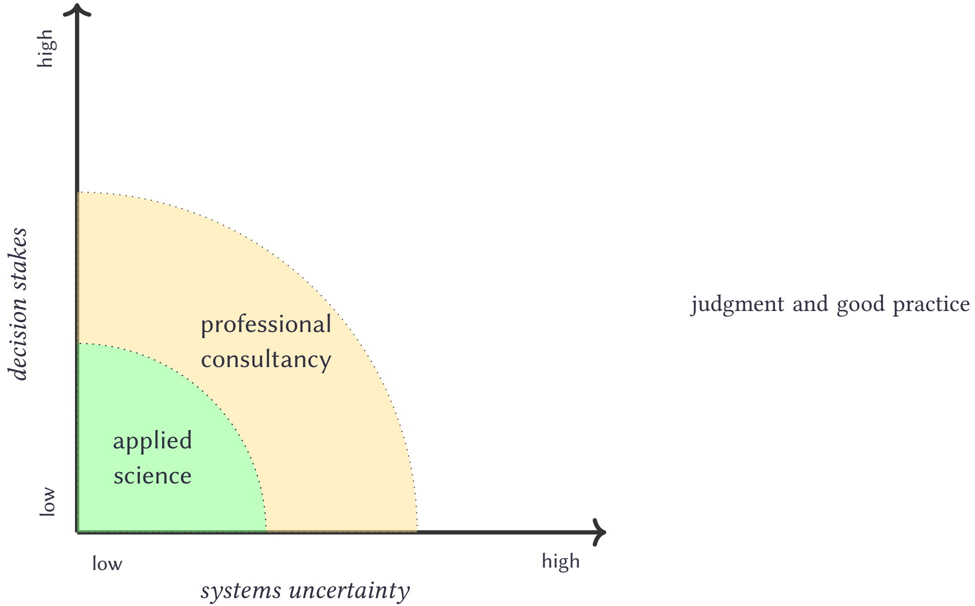


Post-normal science

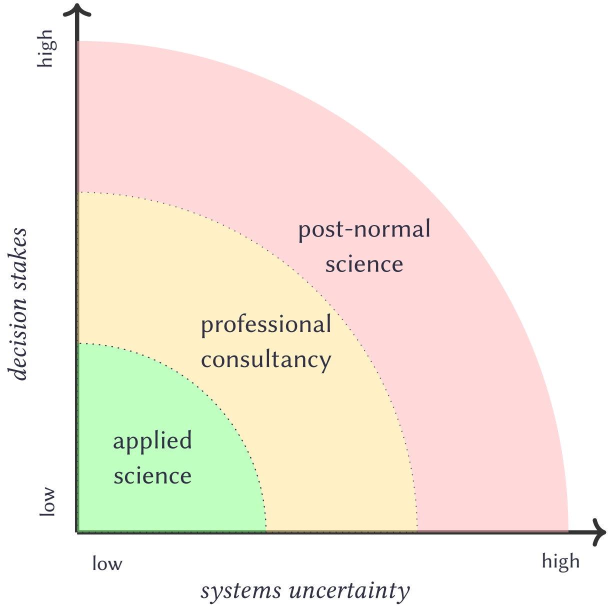


traditional scientific method

Post-normal science

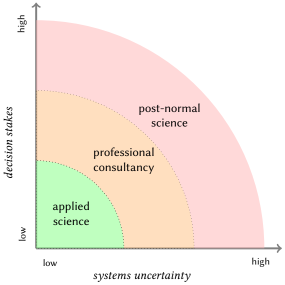


Post-normal science



societal and community consensus and community review

Post-normal science



- **pure research** is motivated by curiosity
- **applied science** is "mission-oriented"
  - uses the traditional scientific method
  - affected by technical uncertainty, which is managed by statistical analysis
- **professional consultancy** is "client-serving"
  - uses professional judgment and good practice
  - affected by methodological uncertainty, which is managed by professional consensus and peer review
- **post-normal science** is "issue-driven"
  - affected by epistemological uncertainty, managed by societal and community consensus and community review
  - quality assurance for scientific information is an acute problem (*cf.* `nusap.net`)

Coping technique: precautionary logics

- Scenarios involving very large potential impacts and uncertainty concerning probability are poorly suited to classical decision-making
  - examples: climate change, GMOs, nuclear war
- These scenarios call for
  - **logics of precaution**, such as Jonas' imperative of responsibility, the precautionary principle, sustainability principles
  - **deliberation about action**: techniques from participatory democracy and social appraisal can provide a complement to existing scientific knowledge concerning an uncertain risk
- Note: the continued failure of international initiatives such as the UN Convention on Climate Change and the UN Convention on Biological Diversity illustrate the difficulties of working together on complex, high-impact but uncertain challenges…

Coping technique: increase resilience

- Limits in knowledge mean we can’t determine the probability of black swan events
- However, we *can* act to limit their impact, by **reducing vulnerabilities**
- Notion of *system resilience*, after E. Hollnagel and D. Woods:
  - ability of a system to adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions
- Characteristics of resilient organizations: ability to
  - **respond** to variability, disturbances and opportunities
  - **monitor** what is going on and identify threats and interpret them
  - **anticipate** possible future outcomes and their potential
  - **learn** from experience

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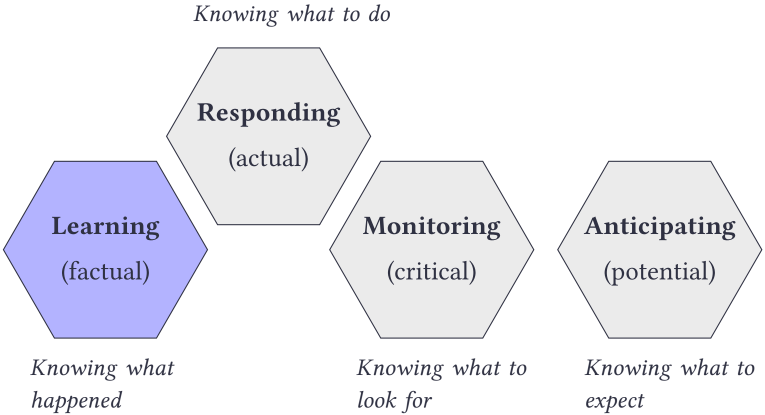
The four cornerstones of resilience

Ability to learn from the past

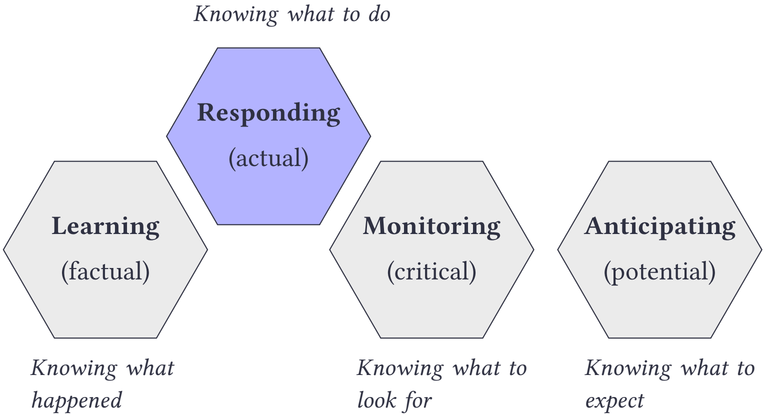


Source: Hollnagel, E. (2011) *Prologue: the scope of resilience engineering*, in *Resilience Engineering in Practice: A Guidebook.* Ashgate

RISK ENGINEERING

The four cornerstones of resilience

Knowing what to do when something happens, either by following previous practices or being able to adjust to the new situation quickly

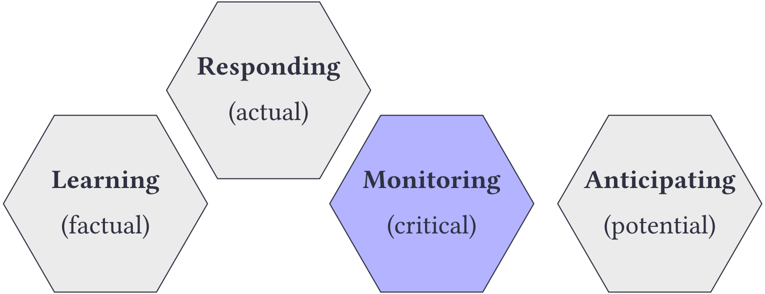


Source: Hollnagel, E. (2011) *Prologue: the scope of resilience engineering*, in *Resilience Engineering in Practice: A Guidebook*. Ashgate

The four cornerstones of resilience

Being able to see the early signs that something is changing and taking timely avoiding action

Knowing what to do



Knowing what happened

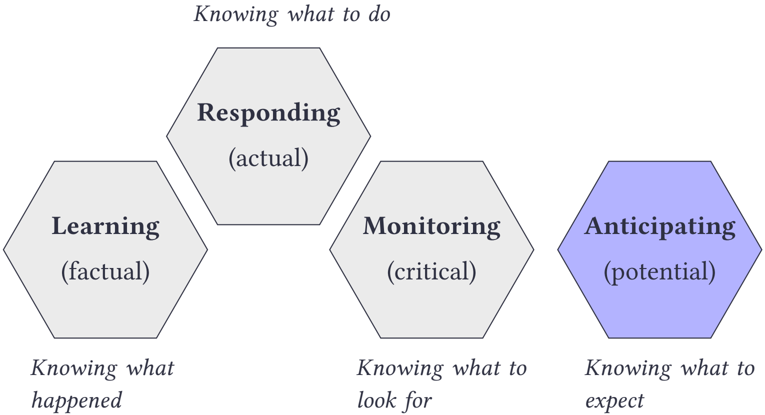
Knowing what to look for

Knowing what to expect

Source: Hollnagel, E. (2011) *Prologue: the scope of resilience engineering*, in *Resilience Engineering in Practice: A Guidebook*. Ashgate

The four cornerstones of resilience

Ability to anticipate what may happen in the future and what effect it will have on the organization



Source: Hollnagel, E. (2011) *Prologue: the scope of resilience engineering*, in *Resilience Engineering in Practice: A Guidebook*. Ashgate

Coping technique: increase resilience

- Lots of research on **resilience engineering** over the past 10 years
  - → `resilience-engineering-association.org`
  - see Eurocontrol White Paper on resilience engineering for ATM
- A related principle developed by the High Reliability Organizations (HRO) group of researchers is **sensitivity to operations**
  - everyone maintains an awareness of what is and isn't working in the system
  - the opposite of complacency on safety matters
  - attention paid to *weak signals* or *early warning signals*
- Related principles from the HRO work which contribute to **collective mindfulness**:
  - reluctance to simplify interpretations
  - preoccupation with failure
  - deference to expertise

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- You talkin' to me? (slide 36): Robert De Niro in *Taxi Driver*, 1976

Further reading

- Book *The Black Swan: The Impact of the Highly Improbable* by N. Taleb (ISBN: 978-0812973815)
- The Threat observatory of Cambridge University's *Center for risk studies*, `cambridgeriskframework.com/taxonomy`
- Book *Managing the Unexpected: resilient performance in an age of uncertainty*, Karl E. Weick & Kathleen M. Sutcliffe, 2007 (ISBN: 978-0787996499)

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