Resilience is an Emergent System Property: A Partial Argument

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Systems[1]

Some systems mentioned in this presentation

- The London Heathrow crash of BA Flight 38 (Boeing 777)
- The Human Body (briefly)
- The financial system built on mortgage equities (briefly)
- Various electricity grids (European, Swiss Railway, North American)
- Air Traffic Control (briefly)
- Autobahnen/freeways/motorways and mass-collision accidents

- The first examples are by way of introduction to phenomenology
- The last three constitute infrastructure

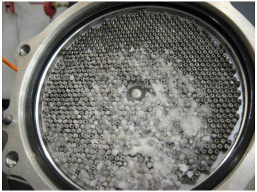
Systems

Basic vocabulary:

- **System:** collection of objects
- ..... with mutual behaviour
- **Behaviour:** change of state
- **State:** properties of objects and relations they have with each other

This suffices as a framework for ontology. Does not magically tell you the things you want to know, such as causal influences.

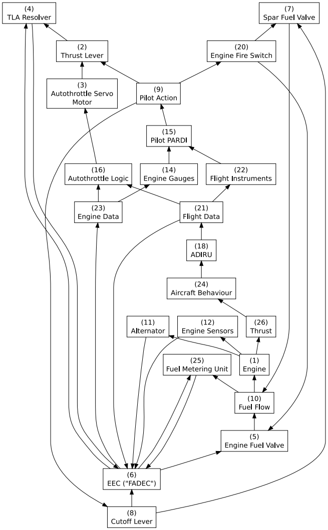
System Operation: Going Wrong in the Large



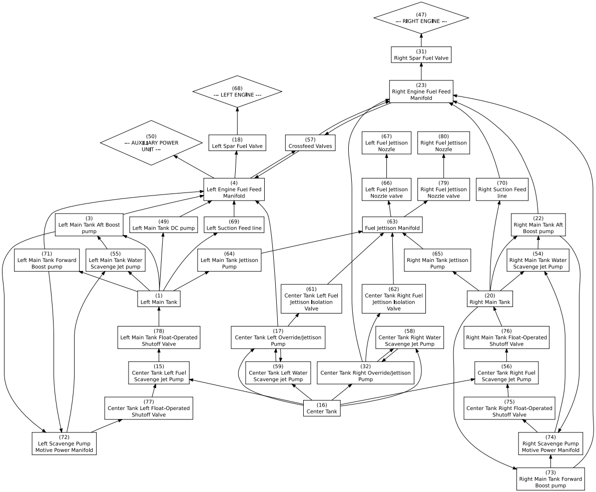
What Happened?

- Insufficient fuel flow on short final
- No physical blockage found upon inspection: ice formation suspected
- Maybe due to unusually cold fuel and atmospheric water vapour at lower altitudes
- Nothing had been broken: Main causal property was *emergent*

Boeing 777 Fuel System: Causal Control Flow Diagram

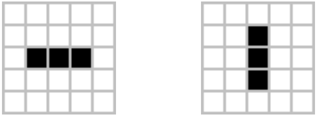


Boeing 777 Fuel Flow



John Conway's *Game of Life*[2]

- two-dimensional grid, discrete time, very simple rules
- emergent properties



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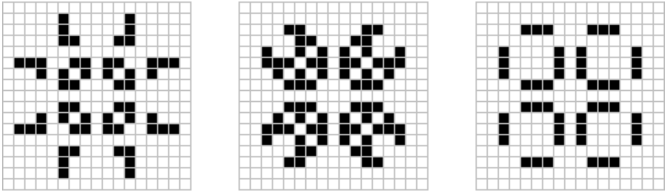

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Speaking of Life: The Human Body

- Large collection of mutually-dependent organisms and subsystems
- If they all die off, your body stops working, for example *digestion*
- very resilient to many small and moderate disturbances, *self-healing*
- *ill* and *well* are emergent properties, described on the phenomenological level
  - the beginnings of a cold
  - runny nose
  - inflamed throat
  - .... which goes away
- much of biomedicine is oriented towards discovering the biological causal basis of these emergent ill/well phenomena
- in engineering, we often have the inverse problem
  - we know the intricate workings in detail
  - we know the emergent properties hardly at all

The Housing Market

- Mortgages were packaged into derivatives
- Those derivatives were sold on
- It became hard to tell what assets were secured and how
- It became hard to tell, ultimately,
  - who could "call in" a loan
  - what security could thereby be appropriated
  - how the security could be divided amongst the creditors
- ... and this not only in the original "repackaged" assets, but also in their derivatives
- since these three matters constitute the risk in a financial instrument, it followed that risk could no longer be assessed

The Housing Market II

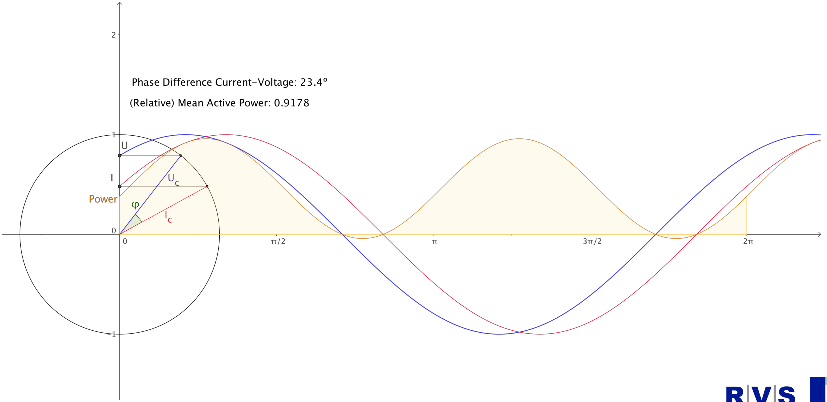
- The larger market is way larger than the US sub-prime mortgage / derivatives market
- If risk can no longer be consensually assessed in existing contracts, then
  - contractual parties can no longer be assured that counterparties can meet their obligations
  - which entails that the risk of new contracts, of whatever sort, can also not be assessed
  - which in turn entails that people are unwilling to make new contracts
  - which in turn entails that the financial market in general reduces and/or collapses
- When the risk in US subprime derivates became no longer assessable, then general market risk became no longer assessable

Emergent System Properties

- *Key observation*:
  it turned out that risk is an emergent property of such markets
  - rather than being an objective property set by established rules
- market-confidence and trust are emergent properties of such markets
  - both causally dependent on perceived-objective determination of risk
  - but also on other factors

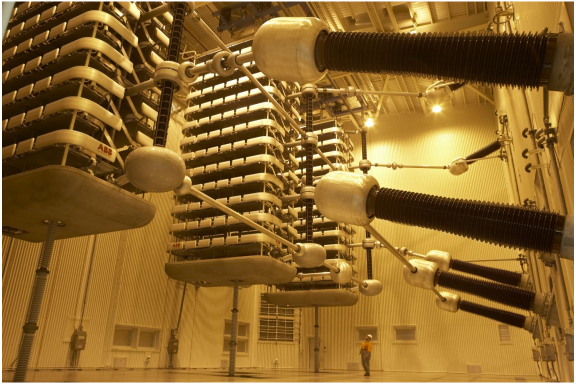
Electricity Grid — Physics I

- Synchronised AC network
- Frequency differences lead to phase differences
- phase differences lead to blind power and reactive power



Electricity Grid — Physics II

- Historic reasons for AC use: much easer to transform voltages
- Still requires huge efforts to convert high-voltage AC↔DC



Electricity Grid — Switching, Monitoring and Control

- High voltage more efficient for transport — low voltage easier and safer to handle for consumers
- Current flows following the laws of Ohm and Kirchhoff laws
- Cross-border-, and inter-company flows are negotiated on free market
- Lines can be switched, generation stations can be turned on and off and regulated
- In an emergency, consumers can be disconnected to preserve grid stability

The European Blackout 4 November 2006[3, 4]

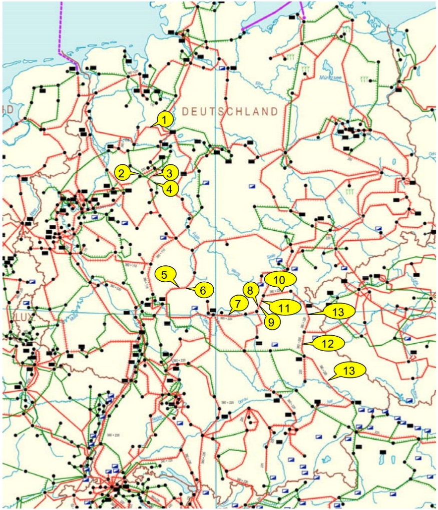
- 15 millions cut off from electricity
- European grid split into three parts
- Triggered by turning off of a 380kV line across the river Ems
- Line turned off to let cruise ship pass

European Blackout — Summary

- Grid operator erroneously assumes grid to be stable with the line turned off
- N-1 criterion was not (re-)checked
- Miscommunication and lack of cross-checking lead operators to make other adjustments
- Many more lines trip in quick succession

Tripping Cascade

Nr.	Zeit	kV	Leitung
1	22:10:13	380	Wehrendorf-Landesbergen
2	22:10:15	220	Bielefeld/Ost-Spexard
3	22:10:19	380	Bechterdissen-Elsen
4	22:10:22	220	Paderborn/Süd-Bechterdissen/Gütersloh
5	22:10:22	380	Dipperz-Großkrotzenburg 1
6	22:10:25	380	Großkrotzenburg-Dipperz 2
7	22:10:27	380	Oberhaid-Grafenrheinfeld
8	22:10:27	380	Redwitz-Raitersaich
9	22:10:27	380	Redwitz-Oberhaid
10	22:10:27	380	Redwitz-Etzenricht
11	22:10:27	220	Würgau-Redwitz
12	22:10:27	380	Etzenricht-Schwandorf
13	22:10:27	220	Mechlenreuth-Schwandorf
14	22:10:27	380	Schwandorf-Pleinting



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European Blackout — Consequences

- Prior to the final tripping of the lines frequencies oscillate
- Grid is split in three, frequencies drift apart
- Consumers in part with under-production have to be disconnected

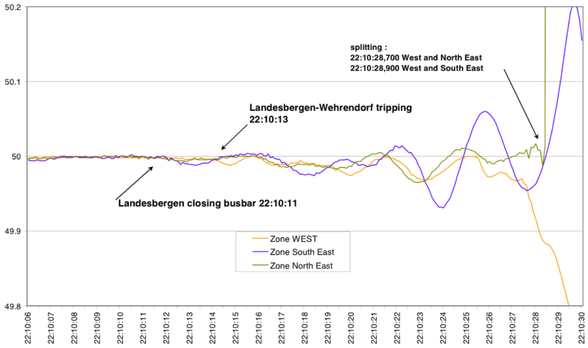

Figure 5: Frequency recordings until area splitting

Figure 6 is presenting frequency recordings as retrieved by Wide Area Measurement Systems (WAMS) in the three areas from 22:09:30 to 22:20:00

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Frequencies — Oscillation, Split, Drift

Just after the split, frequencies quickly drift apart from the nominal 50Hz, precluding a quick reconnection.

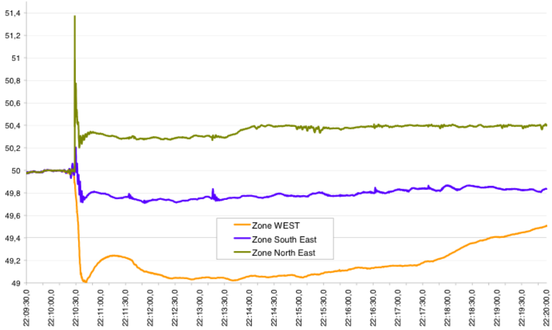


Figure 6: Frequency recordings after the split

The N-1 Criterion

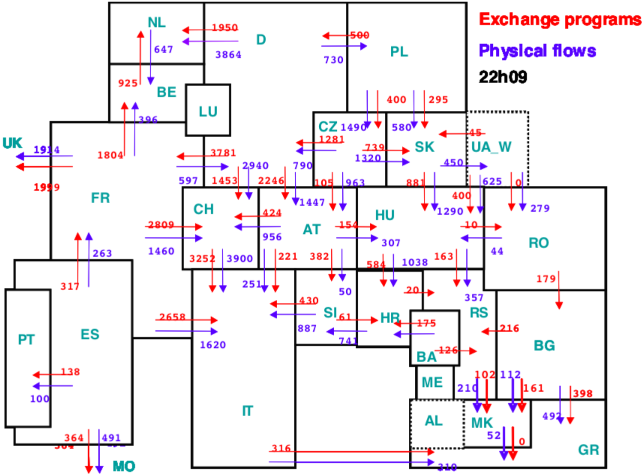
- Described in Operations Handbooks
- States that the net must tolerate failure of one major component and still work securely
- Regulations stipulate that N-1 criterion has to be met at all times
- No detailed description how to guarantee N-1 safety, or how often to perform calculations
- Insufficient specification

Checking for N-1 Safety

- RWE
  - has automated system that performs N-1 calculations every 15 minutes automatically
  - Personnel can easily trigger additional calculation runs
- E.ON
  - No automated system
  - Personnel have to initiate calculations manually
  - Left to Dispatchers' discretion when to perform calculations

Interconnected European Power Grid

- Unevenly distributed generation and consumption
- High-cross-boundary flows of power
- Use of AC requires frequency synchronisation



System Properties

- The European grid was divided into three parts
- Demand is variable, supply sources are regulated as required
- Very short regulation: physically, ca. 10 seconds, change in rotational energy
- After that: primary power regulation, partially automated
- Manual switching when required

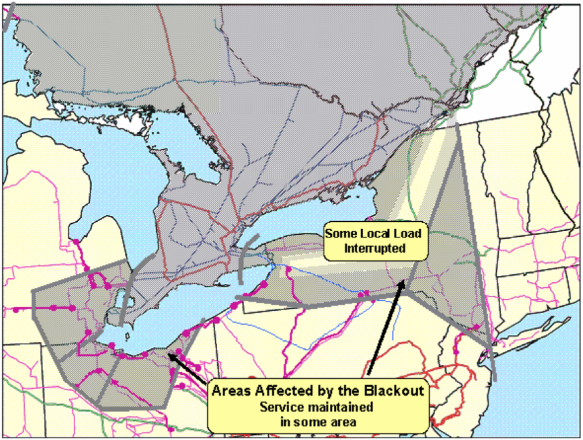
System Properties II

- Computer-assisted flow analysis was available
- Was started automatically at some operaters, not at others
- System is physically resilient only for very short time periods
- After that, frequencies drift too far apart
- Primary power regulation usually automatic in large power stations
- Further actions usually done manually, but rely on accurate and current information

Observations

- Current information of all settings is required
- This information must be coherent among co-operating operators
- Here, neighboring operaters used different cutoff loads for the same line
- Load-redistribution cannot be predicted intuitively
- Available computer assistance was not properly regulated and not used appropriately

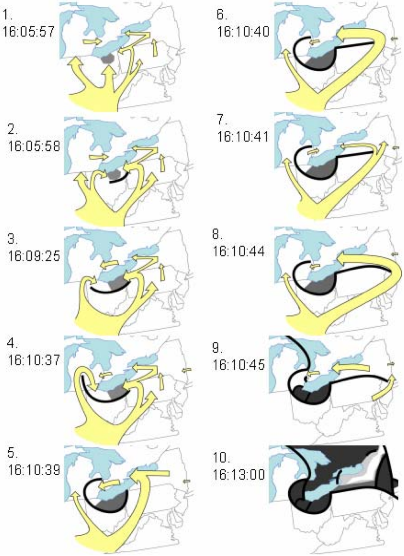
Other Grid Collapses: North American Blackout, August 2003[5, 6]



Graphic: North American Electric Reliability Corporation (NERC)

Power Flows Before the Sammis-Star 345kV line trip

Graphic: NERC



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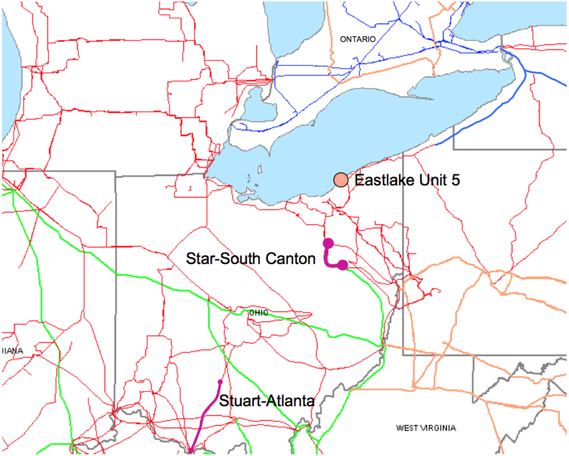
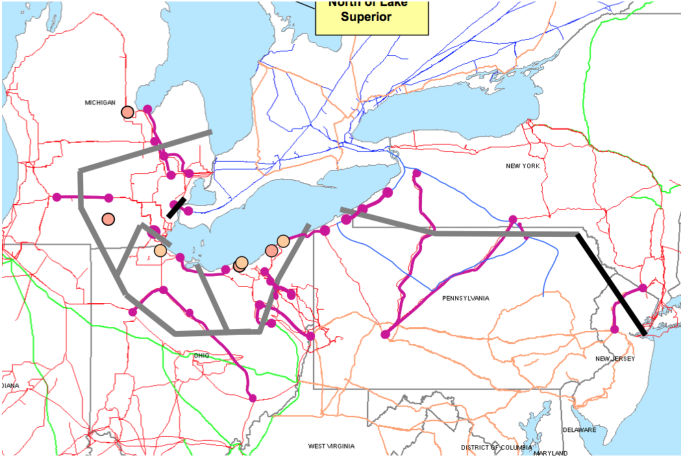
Some Initial Trips Due to Demand from Cleveland-Akron



Graphic: NERC

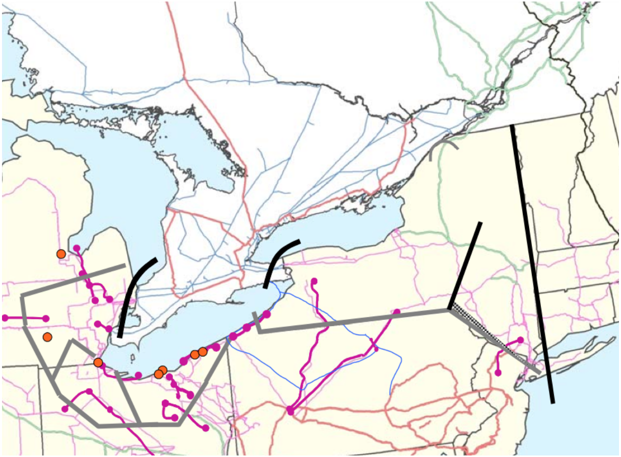
Several more lines trip in succession



Graphic: NERC

NY and New England Separate; Multiple Islands Form

... and eventually



Graphic: NERC

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System Properties

- The North American grid was divided into three parts, Eastern, Western and Texas
- The balance is maintained manually, continually, correct and current information is essential
- stability is defined as having enough resources on-line, in the right places, to satisfy demand
- One operator lost situational awareness
- Computer assistance was inadequate and not used appropriately

Observations

- it seems evident that, had the computer systems worked as intended, grid functionality could have been maintained
- *Key observation*:
  by the Counterfactual Test, the computer failures were causal
  - the computer systems could/should have been designated critical and designed/maintained accordingly

Other Grid Collapses

- The Swiss Railway grid collapsed completely in June 2005 - in 8 seconds elapsed time
- Selected phenomena:
  - the ostensible cause is implausible:
    - very many trains with regenerative braking putting energy into the system simultaneously in one section
    - there does not, however, seem to be any other, more plausible, explanation of the sudden imbalance
  - handling and recovery required all error messages to be manually acknowledged before display refreshed
    - they were coming in way faster than they could be ACKed
    - ⇒ no current and accurate information was available to operators
- WBA by Casten Weber, November 2005

Air Traffic Control

- Normal operation relies on:
  - Secondary Surveillance Radar
  - Radio telephony
  - Co-ordination with adjacent regions / countries
  - Well-trained personnel with good situational awareness
- So far, traffic density is such that the system appears to be resilient to
  - failures of radar coverage in one region
  - failure of main radio system
  - failure of computer systems
- Area can be cleared under contingency protocol
- with backup radio
- with help from adjacent regions
- unclear how resilient it will be with higher traffic density

Mass Motorway Collisions - Auffahr Accidents

- a motorway with non-negligible traffic
- a sudden patch of low visibility
- a mass collision involving tens to nearly hundreds of vehicles

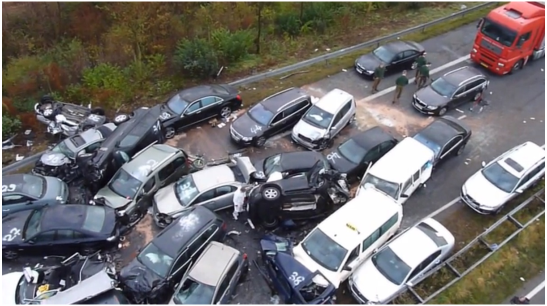

Photo: Uwe Renners (from YouTube video)

Mass Motorway Collisions - Auffahr Accidents

- such auffahr accidents have been regularly occurring for over fifty years
- the "authorities" always search for someone to blame
  - some driver or drivers behaving inappropriately
  - in this case, it was minor - a minor fender bender in fog
- *Key observation*:
  propensity for such accidents is an emergent property of the system
  - they can occur when every driver makes the most rational individual decision given the observable state
  - mostly they don't occur - the unobservable system state is favourable
  - when the system state is unfavourable, they almost-inevitably occur
- auffahr accident analysis by Ladkin, 2011[7]

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Ques- tions?