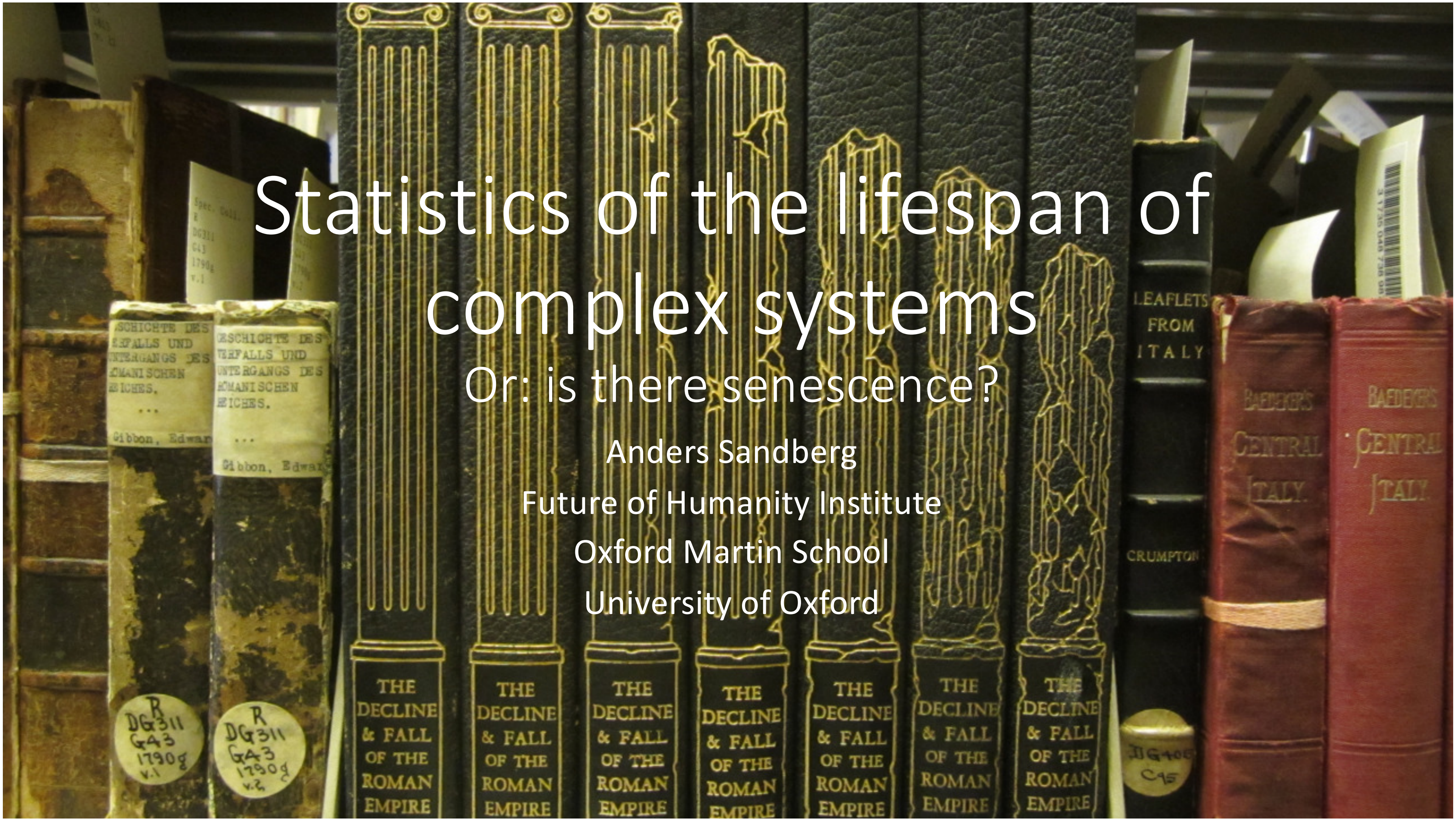
Statistics of the lifespan of complex systems

Or: is there senescence?

Anders Sandberg
Future of Humanity Institute
Oxford Martin School
University of Oxford



My interest: how long-term can projects be?

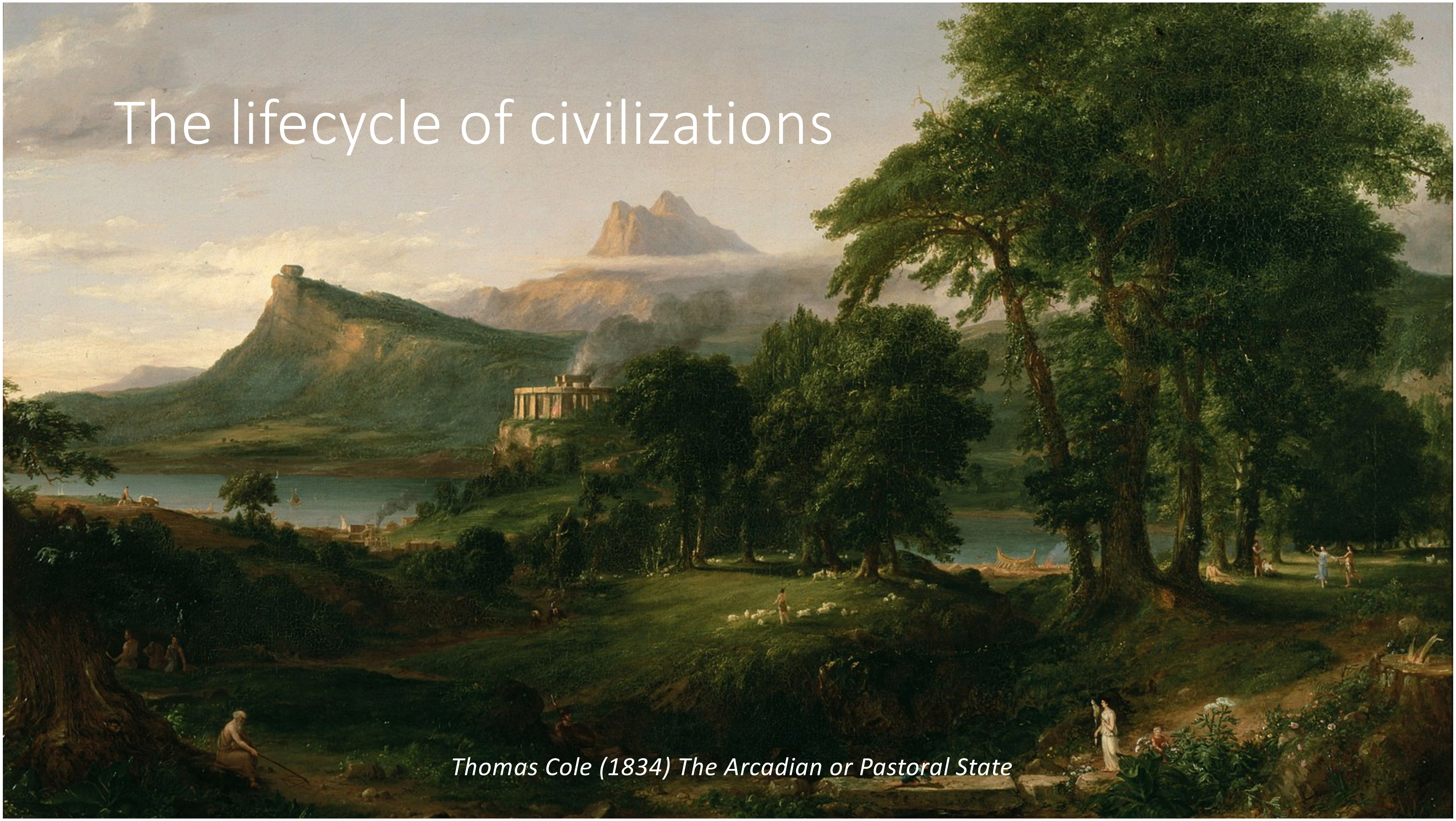
- Are there any "physical" laws that prevent societies from existing indefinitely?

Robert McCall, The Prologue and the Promise (1983)

The lifecycle of civilizations

Thomas Cole (1834) The Savage State

The lifecycle of civilizations



Thomas Cole (1834) The Arcadian or Pastoral State

The lifecycle of civilizations

Thomas Cole (1836) The Consummation of Empire

The lifecycle of civilizations

Thomas Cole (1836) Destruction

The lifecycle of civilizations

Thomas Cole (1836) Desolation

We care about civilization-like complex social organisations

- They can allow the growth of human capital and wellbeing
  - Economies of scale
  - Long-term projects
  - Existential risk reduction?
- Their fall induces significant losses of wellbeing, knowledge, population and may now induce existential risks.

Pieter Bruegel the Elder: The Tower of Babel (c. 1563)

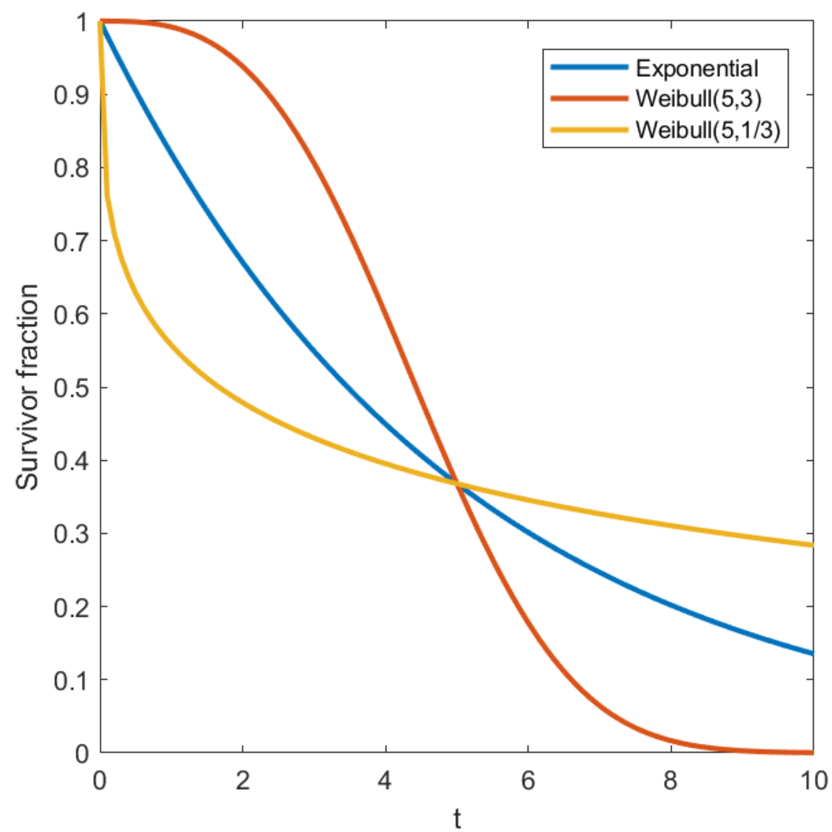
Macrohistorical theories of civilization longevity

- Cyclic theories (ibn Khaldun, Vico, Turchin)
- Decadence (Gibbons)
- Organic ageing (Mommsen, Spengler)
- Entropy (Adams, Georgescu-Roegen)
- Spiritual decline/internal power failure (Toynbee)
- Unsustainable complexity (Tainter)
- Rising energy costs (Homer-Dixon, Rifkin, Garrett)
- Environmental degradation (Diamond)
- Outside invasion
- Disasters, environmental shifts (Diamond)

Increasing risk over time

Is there growing risk?

- Let's test with historical data!
- Null model: constant risk.
  - Survival curve: exponential decline over time.
- Weibull distribution fit: risk growing as t^{k-1} over time.
  - PDF $f(t;k,\lambda) = \left(\frac{k}{\lambda}\right)\left(\frac{t}{\lambda}\right)^{k-1} e^{-\left(\frac{t}{\lambda}\right)^k}$
  - Survival curve: more rectangular ($k > 1$, "ageing") or steeper early decline ($k < 1$, "childhood mortality")
- (Need to consider censoring issues)



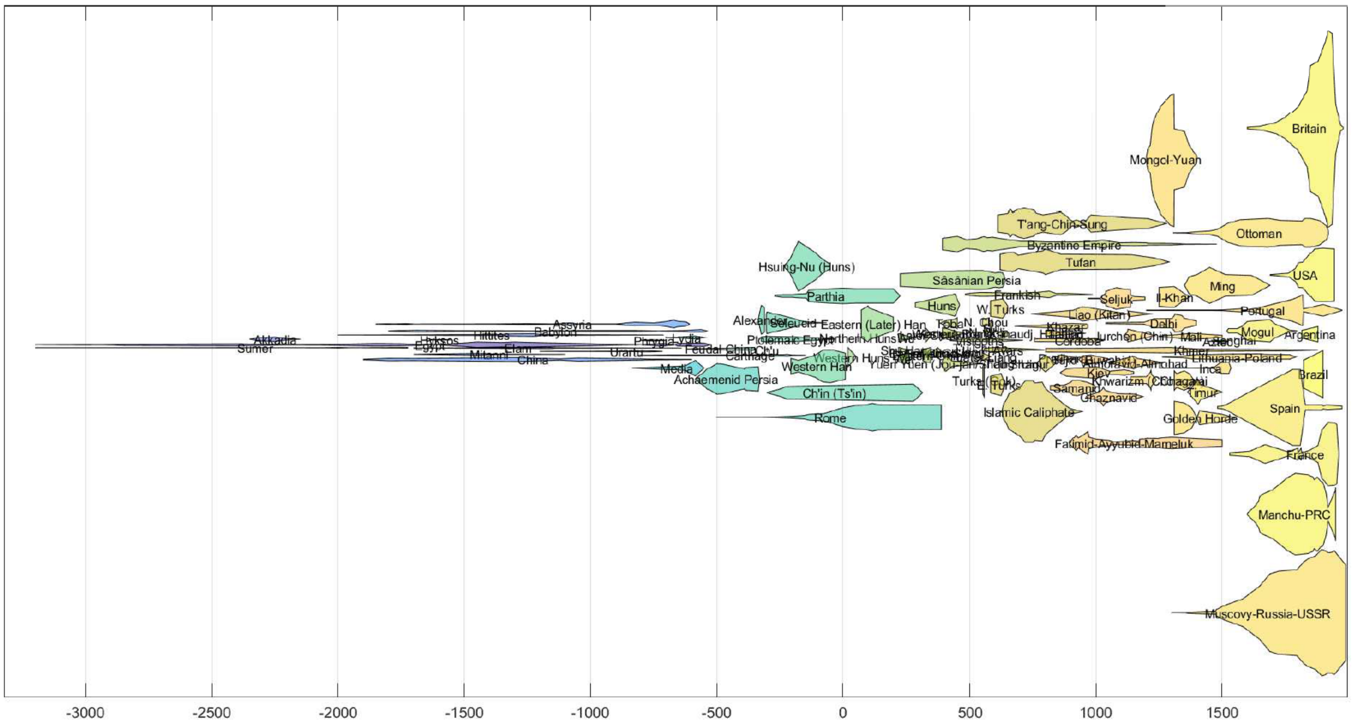
Empires

- Civilizations are badly defined (and probably too few to be statistically significant). What we care for is large transgenerational social organisations
- Solution: use empires and states instead

Thomas Cole: The Architect’s Dream (1840)

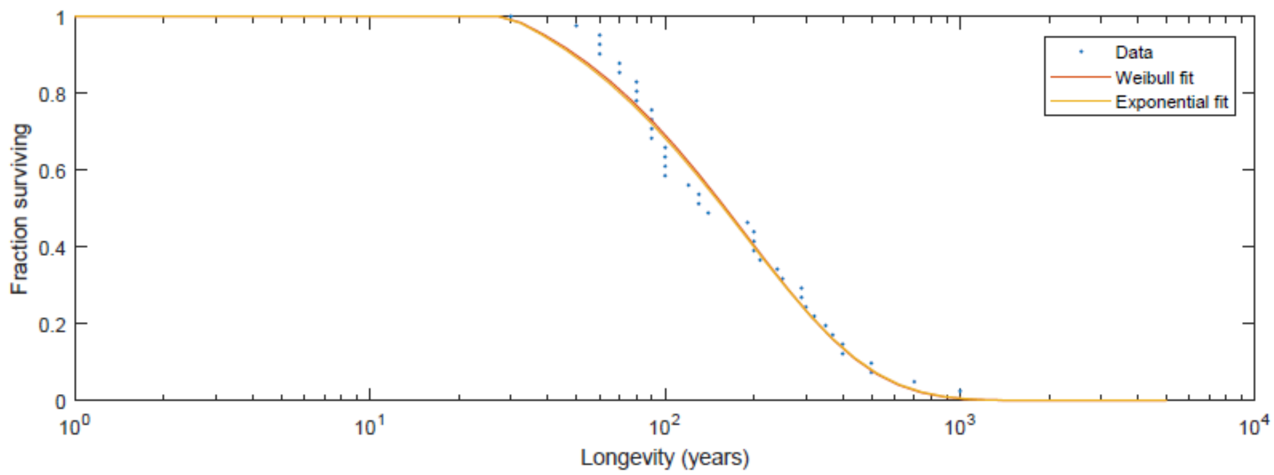
Taagepera empire data

- Rein Taagepera:
  - Empire: “any relatively large sovereign political entity whose components are not sovereign”.
  - 5,000 years of empires.
- Samuel Arbesman (2011): exponential survival curve with half-life 220 years.



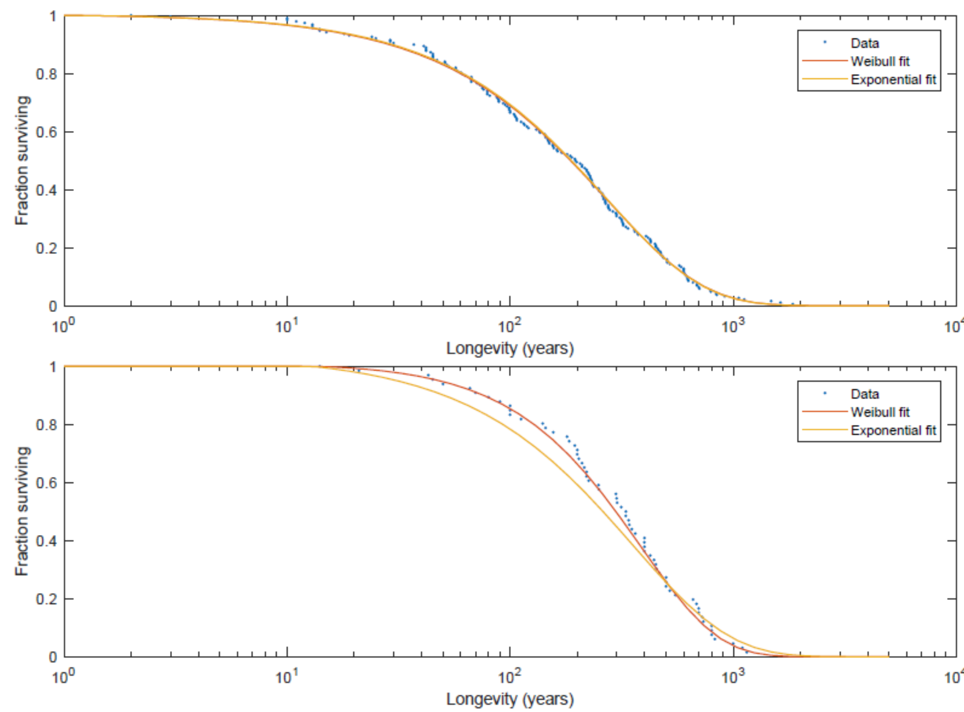
Taagepera empire data

- From start to finish:
  - $\lambda = 348.3815$ and $k = 0.9205$ with 95% confidence interval [0.7869, 1.0768].
  - Hence, cannot reject null hypothesis of no ageing!
- From “adulthood” (80% of max size) to final date:
  - $\lambda = 188.1137$ years and $k = 1.0217$. No ageing!
- No trend over time (!)



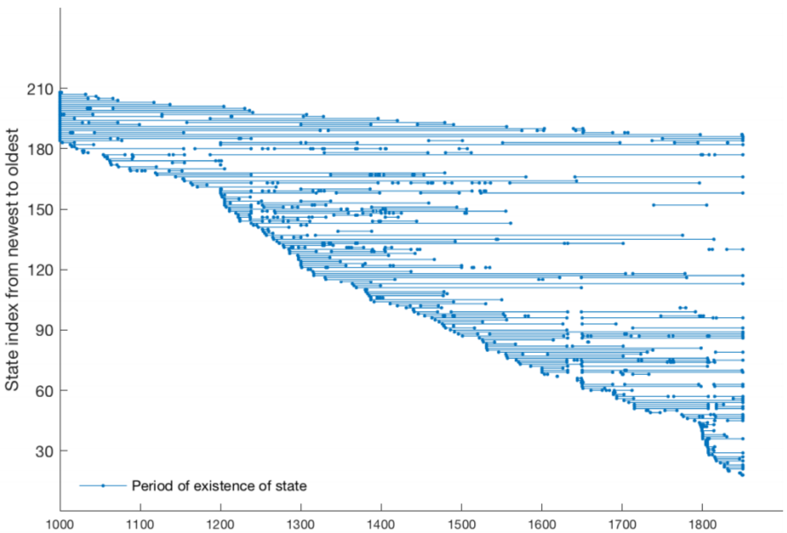
Other empire sets

- Wikipedia's list of empires: $\lambda = 270.9173$ years and $k = 0.9986$ with 95% CI [0.8951, 1.1141]. No ageing.
- Estimates by Larry Freeman on his blog of the durations of ancient civilizations/empires: $\lambda = 381.8091$ years and $k = 1.2500$ with a 95% CI [1.0294, 1.5177]. Mild ageing, nearly nonsignificant.

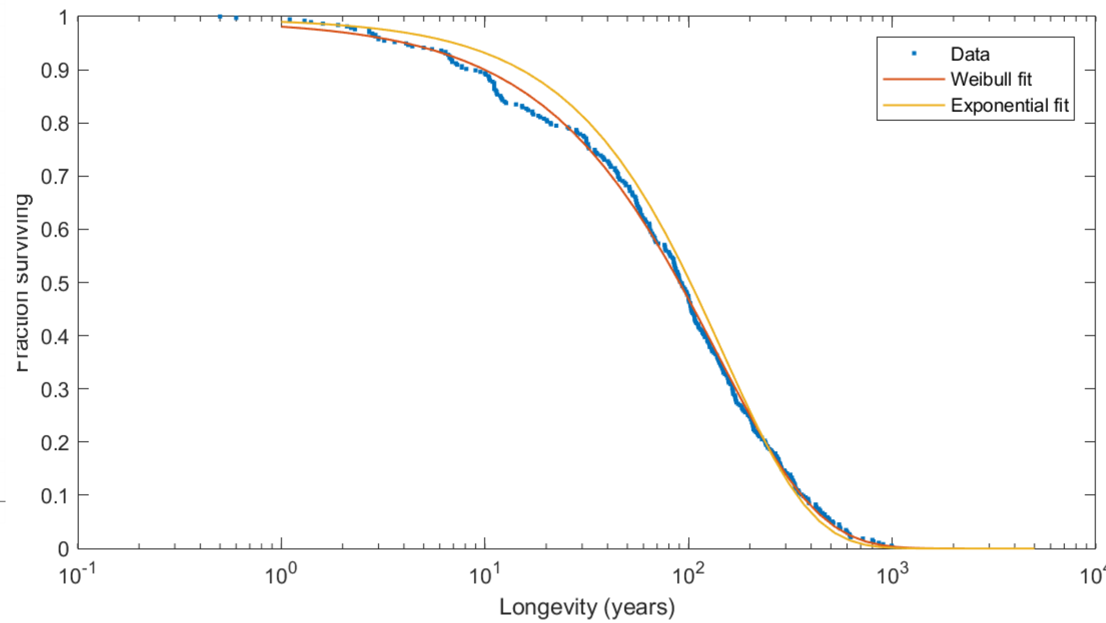


States Europe 1000-1850

- Data courtesy of Schönholzer and Weese, based on Bairoch.
- $\lambda = 136.6277$ years and $k = 0.8604$ with 95% CI [0.7950, 0.9312]: a bit of childhood mortality!

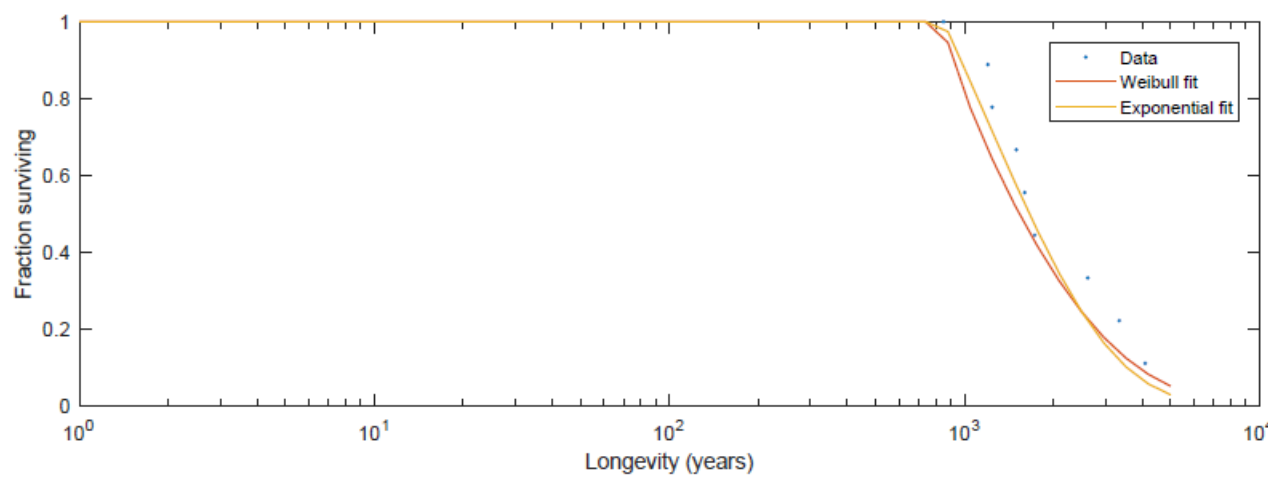


Notes: Entry, existence and exit of European states with at least one city as defined by Bairoch over 1000-1850 according to the coding in Reed (2016). States are ordered by index from top to bottom by year of entry, and within those, year of exit.



World systems

- World systems theory/perspective (Wallerstein, Chase-Dunn)
- 9 past civilizations/world systems listed by Wilkinson.
- $\lambda = 1080.7$ years (they persist far longer than their individual component empires) and $k = 0.8083$, CI [0.4611,1.4169].
- No clear ageing, but little data.

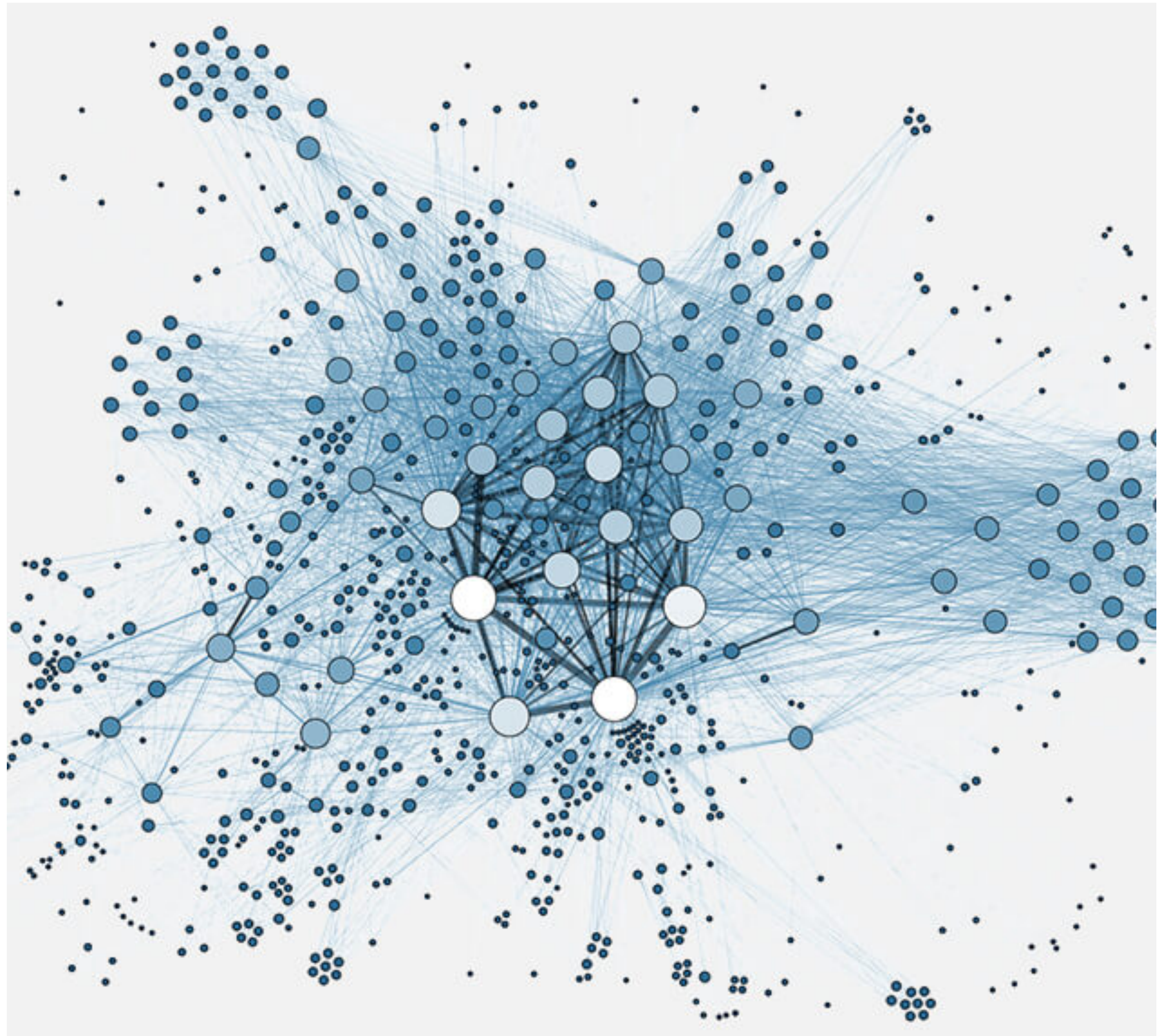


Human big social organisations

- At least in this data, no clear sign of senescence: risk is constant over time.
- Caveat: this has been *lifespans* rather than *time to collapse.*
- Maybe collapses have different distribution.
- But I would need a definition of which case is a collapse to test.

Complex adaptive systems

- States, societies, civilizations are all CAS.
- Background assumption: maybe there are joint rules for large classes of CAS.
  - (Background worry: maybe everything is just individual cases because of “wild” properties.)
- What kinds of CAS show limited lifespans?



Firms

- Exponential survival curve
  - Independent of business sector
  - Size at birth has positive correlation longevity
  - Liability of newness and adolescence
- $\lambda \approx 10$ years for current corporations, $\lambda \approx 170$ years for extreme tail
- Liabilities at bankruptcy power-laws, but longevity exponential (Fujiwara 2004)
- Sales and costs closely balanced? (West 2017)

Daepp, M. I., Hamilton, M. J., West, G. B., & Bettencourt, L. M. (2015). The mortality of companies. *Journal of The Royal Society Interface*, *12*(106), 20150120.

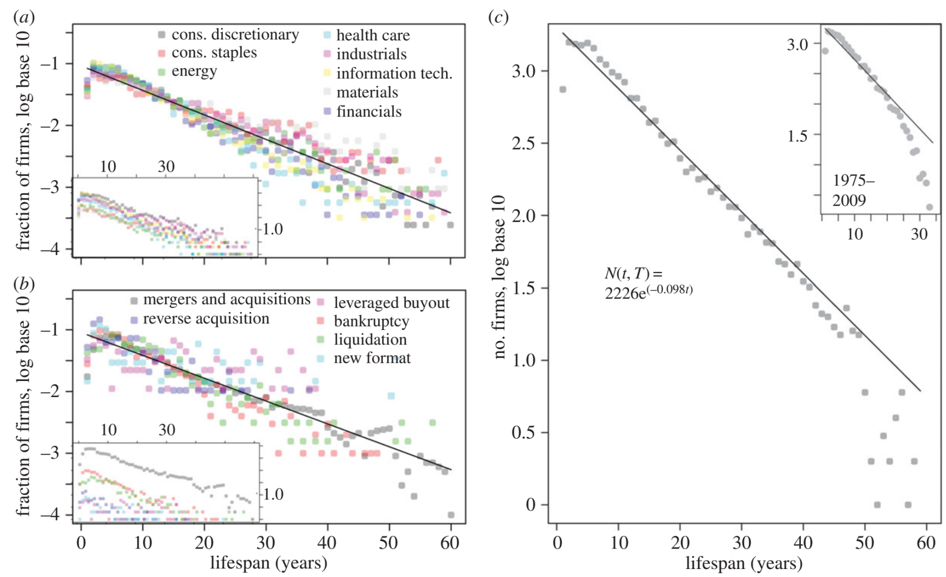


Figure 2. Frequency distribution of firm lifespans. The frequency distribution of firm lifespans is approximately exponential, independent of business sector. Colours denote firms from different economic sectors (*a*) and with different reasons of death (*b*) for the period 1950–2009. Insets show the lifespan frequency distributions before normalization by sector size. In (*b*), the reasons 'other' and privatization were omitted; in (*a*), the telecommunications, utilities and transportation sectors were omitted based on small sample size. The aggregate distributions are fit by a simple exponential function shown in (*c*). For the full window, the fit is $N(t, T) = 2226e^{-\lambda t}$ with $\lambda = 0.098$ and 95% confidence interval [0.093, 0.104]. For the constrained window, the fit is $N(t, T) = 2279e^{-\lambda t}$ with $\lambda = 0.131$ and 95% confidence interval [0.123, 0.140].

Species

- Van Valen's law of constant extinction
  - Appears true in many but not all cases
  - Complications due to fossil record, clades
  - Explained by one of the variant Red Queen Hypotheses?
- Žliobaitė, Fortelius & Stenseth: extinction due to abiotic factors, biotic competition for spatial spread.

Pearson, P. N. (1995). Investigating age-dependency of species extinction rates using dynamic survivorship analysis. *Historical Biology*, *10*(2), 119-136.

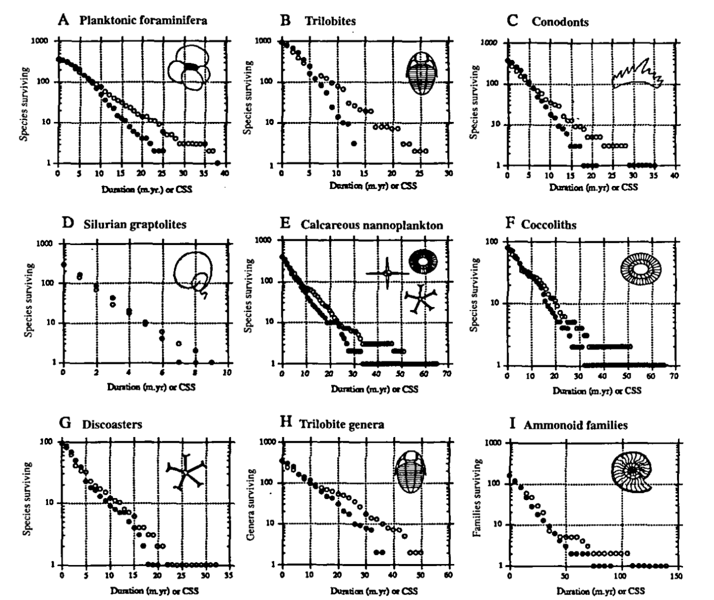
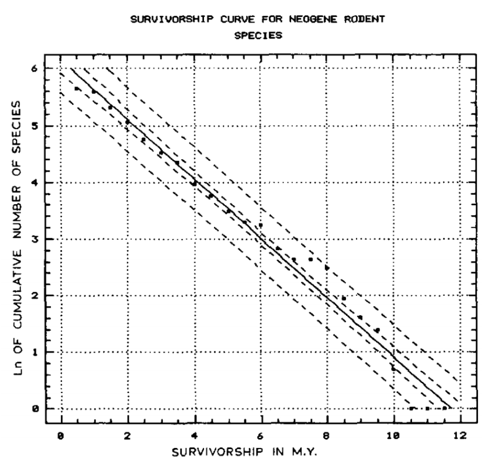


Figure 2 Survivorship curves for nine fossil groups (data-sets as fig.1). Filled circles: CSS curves. Open circles: uncorrected curves.

Jaeger, J. J. (1994). The evolution of biodiversity among the Southwest European Neogene rodent (Mammalia, Rodentia) communities: pattern and process of diversification and extinction. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *111*(3-4), 305-336.

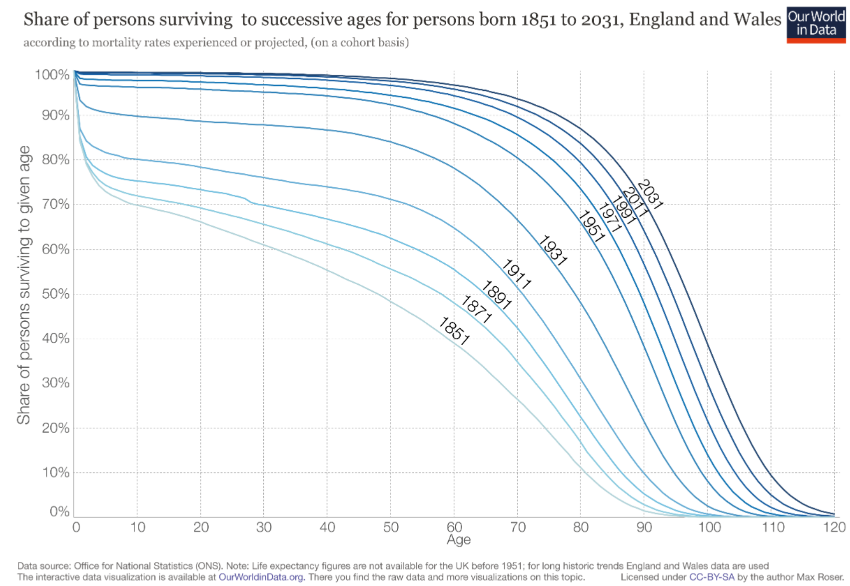


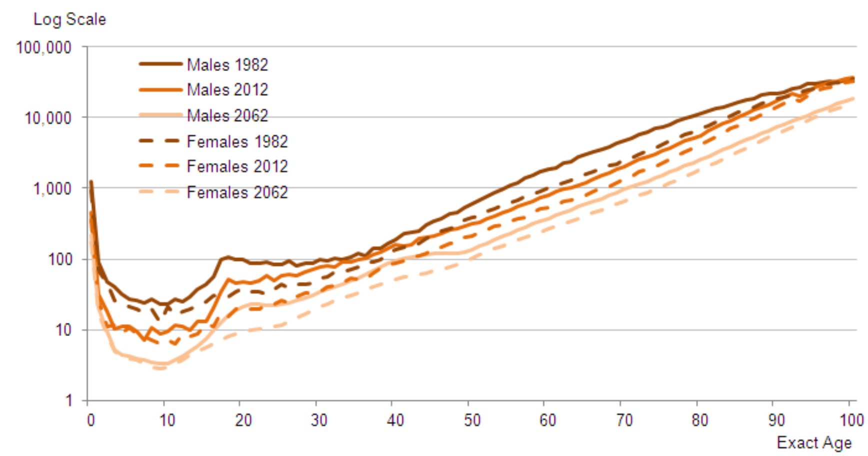
Unclear cases

- Institutions?
  - Multi-century universities.
  - Multi-millennia religious orders.
  - Too little data for the long-lived ones.
- Cities?
  - Jericho 9,000BC, fortifications from 6,800 BC.
  - Geoffrey West: renewing economies of scale?

Biological ageing

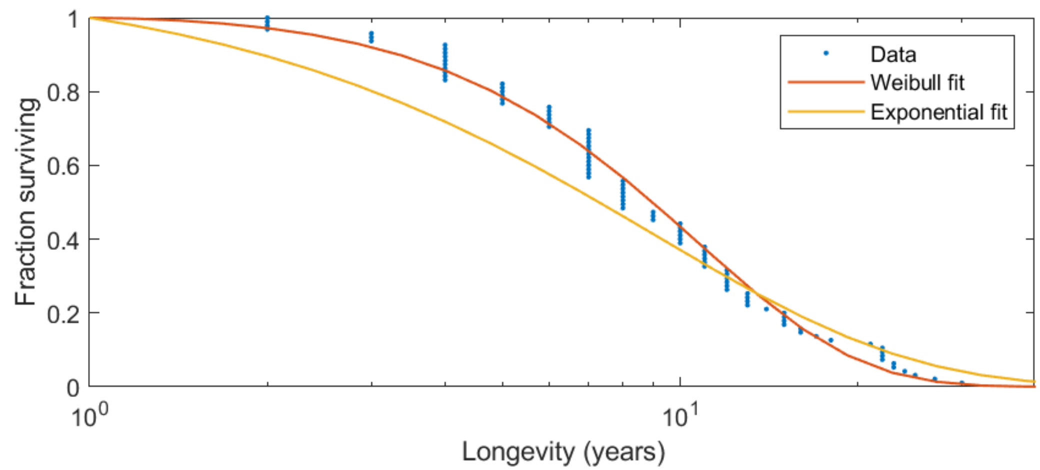
- Senecense common in multicellular organisms.
- But exceptions in some species: Perennial angiosperms, Blanding's turtle, Olm, eastern box turtle, red sea urchin, rougheye rockfish, ocean quahog clam, bristlecone pine...



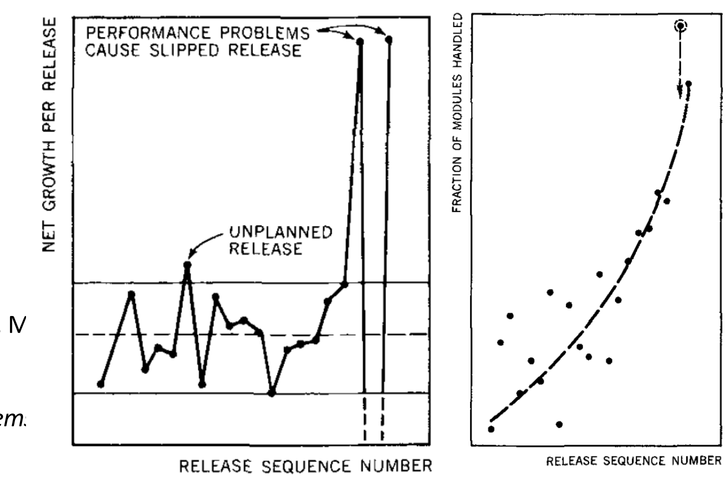


Software

- Japanese corporate systems $\lambda \approx 11.4$ years, $k \approx 1.7$
- Meir Lehman's laws of software evolution: unless work hard to counter it, maintainability will go down due to growing entropy/complexity.
  - *“Law of continuing change.* A system that is used undergoes continuing change until it is judged more cost effective to freeze and recreate it. “
  - *“Law of increasing entropy.* The entropy of a system (its unstructuredness) increases with time, unless specific work is executed to maintain or reduce it. “



Belady, L. A., & Lehman, M M. (1976). A model of large program development. *IBM System journal*, *15*(3), 225-252.

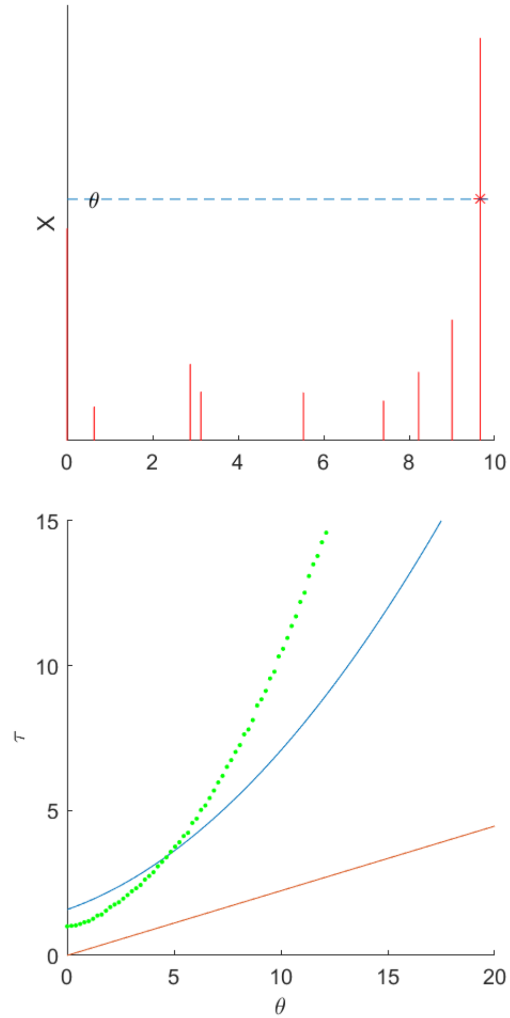


CAS ageing

- Causes:
  - Evolution can produce ageing because of genetic drift
  - Growth and unmitigated complexity
- Not at all universal: many non-ageing CAS
- Competition does not cause ageing
- But why should *lack* of ageing be common, either?

A simple model of constant risk

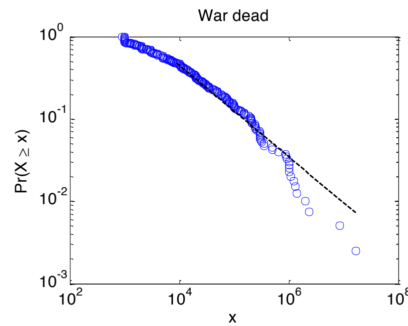
- Random challenges happens at rate λ with severity $\mathrm{X} \sim f(x)$.
- X has complementary cumulative distribution function $\bar{F}(x) = \Pr[X > x]$.
- System has resistance level θ, will survive if $X < \theta$.
- System survives a geometrically distributed number of challenges with parameter $\bar{F}(\theta)$.
- Expected time of survival: $\tau = \frac{1}{\lambda \bar{F}(\theta)}$.
- Markov inequality $\bar{F}(x) \leq E[X]/x$ gives the bound $\tau \geq \frac{\theta}{\lambda E[X]}$ if $E[X]$ exists.
- One-sided Chebyshev inequality $\bar{F}(x - E[X]) \leq \frac{\sigma^2}{\sigma^2 + x^2}$ gives the bound $\tau \geq \frac{1}{\lambda}\left(1 + \frac{(\theta + E[X])^2}{\sigma^2}\right) \propto \theta^2$ if variance σ^2 exists.
- If $f(x)$ is heavy-tailed all bets are off. Weak dependence on θ!

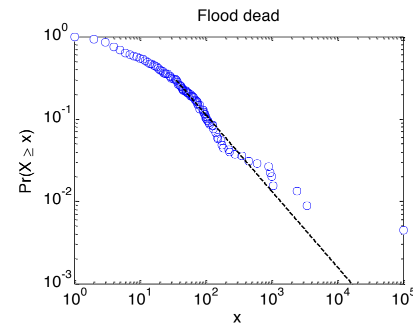


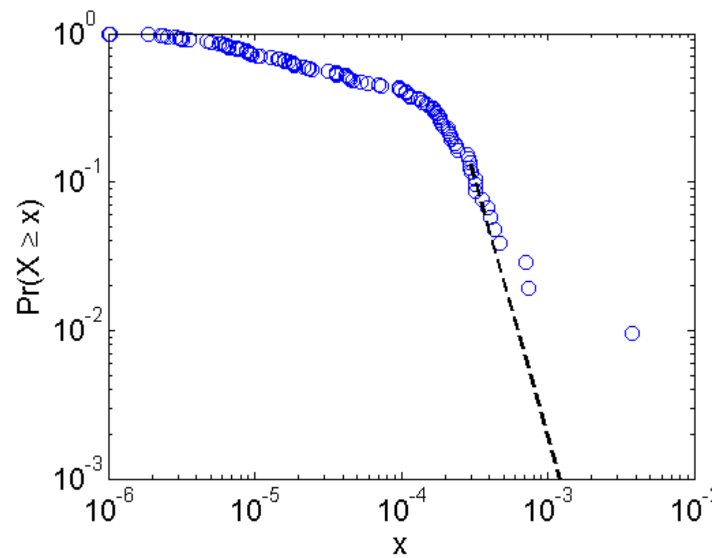
Heavy tail distributed risks are common

- Natural disaster fatalities (earthquakes, volcanos, floods, tsunamis…)
- Richardson law of war fatalities.
- Pandemic outbreak sizes?
- If combining several, most extreme tail dominates.

- For extreme Pareto distribution, survival time *independent* of θ





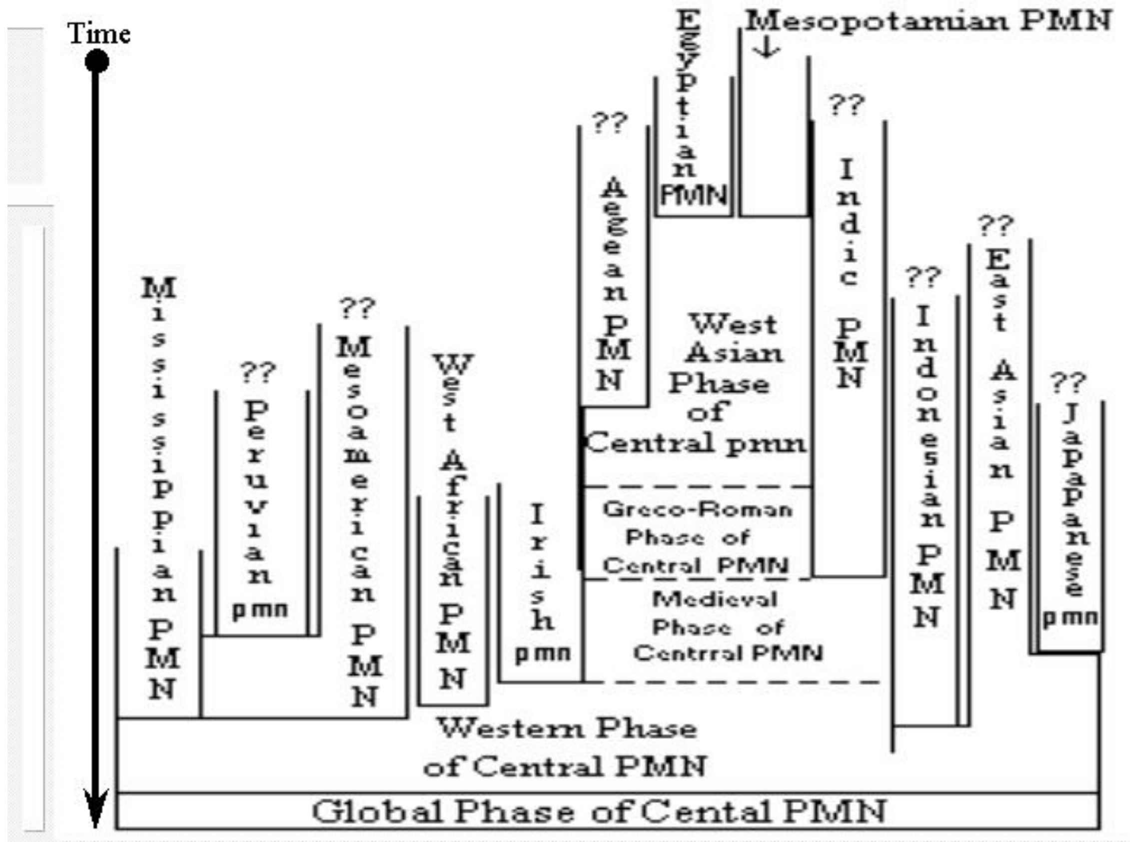


Synthesis: collapse as *combined* bad luck

- The disasters are mixtures of very extreme events or combinations of factors.
- Hard to avoid (unprecedented or rare confluences, “black swans”)
- Competitive pressures (cost, alternative costs, competition) lead to finite θ. But even large θ insufficient against tail risks.

Central system idea

- Wilkinson: a “central system” of merging political-military networks has grown by mergers and expansion over 7,500 years
- Shklovskii & Sagan: “The present technical civilization of the planet Earth can be traced from Mesopotamia to Southeastern Europe, to Western and Central Europe, and then to Eastern Europe and North America.”



Chronograph of the Rise of the Central System

What does this tell us about our fragility?

- Maybe less than we would wish: we are the first global, high-tech civilization. We have good reasons to be concerned.
- But there is apparently no unavoidable law forcing *decline* on us.
- The Central System has been around for 7,500 years. We have rebuilt ever higher. But having backups sounds like a good idea.

Robert McCall, The Prologue and the Promise (1983)