"Complex Systems Theory, Sustainability and Innovation"

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The ‘Anthropocene’

• Human societies define what they see as their environment
  – They define its perimeter and characteristics
  – They define its challenges
  – They define and create potential solutions
• Over the last few centuries, they also have come to control their environment
• How did that come about?
• What are the implications?
The apparent results …
The apparent limits

- $\text{CO}_2$
- Methane and other nitrogen gases
- Ocean acidification
- Biodiversity
- Phosphorus and sulfur cycle
- Ozone depletion
- Freshwater use
- Aerosol loading
- Chemical pollution
- Land use change

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Humans are part of a complex adaptive system...

- The Earth system is a complex adaptive system
- Human societies are an integral part of it
- Such systems are characterized by high dimensionality:
  - Multiple attractors
  - Open-ended trajectories
  - Tipping points and unstable phases
  - Absence of long-term predictability
- How we deal with it has varied through time
Humans organize

• Many animals can learn in limited ways
• Humans can do more:
  – Experiment
  – Devise abstract, communicable symbols
  – Learn how to learn, and cumulate learning
  – Organize themselves, and their social and natural environment
• All and everything humans do is organize
  – We need to adopt an organization perspective
Every society is an information society

- Information is not subject to the conservation principle: it can be shared and spread
- Energy and matter cannot be shared but are necessary for human survival
- People harness energy by transforming the organization of their environment
- Societies are held together by the information they process; energy is a constraint
What has driven the great acceleration?

• Which questions do the ‘hockey-stick’ curves pose?
  – Why did ‘it’ take so long?
  – Why did ‘it’ go so fast, once ‘it’ got going?
  – What is ‘it’?

• ‘It’ is not the climate or the environment, but the innovative capacity of society
  – What is different about humans that they can develop complex technologies?
  – Are the enabling factors biological or socio-cultural?
Pleistocene Climate is unstable

Climate change was dramatic, but cultural change was minimal

Why is that so?
Stage 1: Evolution of STWM

- STWM differs between humans and primates & other animals
- Direct evidence: size of adult STWM impacts on operations
  - Chimpanzee nut cracking involves 3 objects (anvil, nut, hammer)
  - 25% of chimpanzees never learn to do this: STWM is 2 +/- 1
  - Other tests point to same: token combinations, object manipulation, gesture combinations
  - Modern human STWM is 7 +/- 2
- Indirect evidence:
  - STWM development
  - Encephalization
STWM develops with age

Trend line projected from Time Delay Response regressed on Infant Age (see inset). Data rescaled for each data set to make trend line pass through mean of that data set. Working memory scaled to STWM = 7 at 144 months.

Fuzzy vertical bars compare age of nut cracking among chimpanzees with age for relative clause acquisition and Theory of Mind conceptualization in humans.
Encephalization takes time

Graph of encephalization quotient (EQ) estimates based on hominid fossils and Pan (Chimpanzees). Early hominid fossils have been identified by taxon. Each data point is the mean for hominid fossils at that time period. Height of the ‘fuzzy’ vertical bars is the hominid EQ corresponding to the data for the appearance of the stage represented by the fuzzy bar. Right vertical axis represents STWM. Data are adapted from the following: triangles: Epstein 2002; squares: Rightmire 2004; diamonds: Ruff et al. 2004. EQ= brain mass/(11.22 body mass^{0.76}), cf. Martin 1981.
Artifacts and STWM development

• Size of STWM is constraint on cognitive complexity of early artifacts
  – Derive from conceptual complexity of artifacts indication of size of STWM
  – The simplest conception of an artifact is a combination of geometric and topological properties
    • Example: Oldowan chopper conceived as cutting line made by repeating ‘point’ flaking

• Cognitive complexity of stone tool conception is indicator for STWM development

• Similar arguments made for language development and abstraction in kinship systems

• Next slide shows evolution
## Evolution of stone tool technology

<table>
<thead>
<tr>
<th>Stage</th>
<th>Concept</th>
<th>Action</th>
<th>Novelty</th>
<th>Dimensionality</th>
<th>Goal</th>
<th>Mode</th>
<th>ST</th>
<th>WM</th>
<th>Age BP</th>
<th>Example</th>
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<tr>
<td>1</td>
<td>Object attribute</td>
<td>Repetition possible</td>
<td>Functional attributes already present; can be enhanced</td>
<td>0</td>
<td>Use object</td>
<td>1</td>
<td></td>
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<tr>
<td>1A</td>
<td>Relationship between objects</td>
<td>Repetition possible</td>
<td>Using more than one object to fulfill task</td>
<td>0</td>
<td>Combine objects</td>
<td>2</td>
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</tr>
<tr>
<td>2</td>
<td>Imposed attribute</td>
<td>Repetition possible</td>
<td>Object modified to fulfill task</td>
<td>0</td>
<td>Improve object</td>
<td>2</td>
<td>&gt; 2.6 My</td>
<td>Lokalalei 1</td>
<td></td>
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<tr>
<td>3</td>
<td>Flaking</td>
<td>Repetition</td>
<td>Deliberate flaking, but without overall design</td>
<td>0: Incident angle &lt; 90º</td>
<td>Shape flakes</td>
<td>3</td>
<td>2.6 My</td>
<td>Lokalalei 2C</td>
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<tr>
<td>4</td>
<td>Edge</td>
<td>Iteration: each flake controls the next</td>
<td>Débitage: flaking to create an edge on a core</td>
<td>1: Line of flakes creates partial boundary</td>
<td>Shape core</td>
<td>1</td>
<td>2.0 My</td>
<td>Oldowan chopper</td>
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<tr>
<td>5</td>
<td>Closed Curve</td>
<td>Iteration: each flake controls the next</td>
<td>Débitage: flaking to create an edge and a surface</td>
<td>2: Edges as generative elements of surfaces</td>
<td>Shape surface from edge</td>
<td>2</td>
<td>2.0 My</td>
<td>Oldowan chopper</td>
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<tr>
<td>5A</td>
<td>Surface</td>
<td>Iteration: each flake controls the next</td>
<td>Façonnage: flaking used to make a shape</td>
<td>2: Surfaces intended elements, organized in relation to one another</td>
<td>Shape surface from surfaces</td>
<td>2</td>
<td>500 Ky</td>
<td>Biface handaxes</td>
<td></td>
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<tr>
<td>6</td>
<td>Surface</td>
<td>Algorithm: removal of flake prepares next</td>
<td>Control over location and angle of flaking to form surface</td>
<td>2: Surface of the flake brought under control but shape constraint</td>
<td>Serial production of tools</td>
<td>3</td>
<td>300 Ky</td>
<td>Levallois</td>
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<tr>
<td>7</td>
<td>Intersection of planes</td>
<td>Recursive application of algorithm</td>
<td>Prismatic blade technology; monotonous process</td>
<td>3: flake removal retains core shape – no more shape constraint</td>
<td>Serial production of tools</td>
<td>4</td>
<td>&gt; 50 Ky</td>
<td>Blade technologies</td>
<td></td>
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</tbody>
</table>
Palaeolithic stone tool evolution

Oldowan chopper
Acheulean handaxe
Mousterian handaxe
Levallois tool
Solutrean blade

More is different

02/27/2012
The hunter-gatherer way of life

• Throughout the Pleistocene, humans survived through the (Ice) ages, by
  – Harvesting the environment’s offerings
  – A multi-resource strategy
  – Adapting to change by moving
  – Staying below the environment’s carrying capacity
    • Australian famines only in river valleys

• And that, without much change in behavior:
  – People lacked the know-how to interact with their environment; they could only react to it
  – Change and risk were the order of the day
  – Yet people minimized change
    • Epirus caves inhabited where tectonics keep change limited
Stage 2 ‘Tools for thought’

• STWM of 7 +/- 2 is sufficient for all cognitive needs of Modern Humans (*Homo sapiens sapiens*) to date (but how about the future?)
  – Biology no longer a constraint!
  – That constraint explains slow evolution up to this point, acceleration from now on!

• Explosion of new operations
  – Are there other constraints?
  – What are the consequences of acceleration?
Tools available c. 35,000 years BP

- Distinguish between reality and conception
- Categorization based on similarities and differences
- Feedback, feed–forward and reversibility
  - Memory and control loops
  - Mental generation of events potentially to be inserted in operations
- Basic hierarchies
  - Point-line-surface-volume
  - Size (hierarchy of scales)
  - Control loops
- Partonomy
  - Reversal between core and flakes as tools
- Sequentiation and anticipation
  - Separation between stages of production
Mesolithic/Neolithic tools

- Magdalenian tools
- Later Mesolithic tools
- Mesolithic composite tools (reconstructed)
- Neolithic axes
- Neolithic fish trap
- Neolithic basketry (reconstructed)

02/27/2012 More is different
New tools c. 10 Ky BP

- Control over shape complete
  - Flake removal from large to small, polishing
- New topology
  - Solid around void: pots, baskets, houses
    - Separation of concepts of surface and volume
    - Tangled hierarchy of concepts: surface defining volume is defined by other volume
- Inversion of sequence of manufacturing
  - From small to large
    - Assembling instead of removing
- Stretching temporal sequences
  - Separate stages of manufacturing
Stage 3: socio-environmental co-evolution

Change accelerates when the climate is stable

Why?

After Robert A. Rohde, Global Warming Art
The village way of life

• A fundamentally different one…
  – Change in subsistence base: cultivation, herding
  – New technologies: ceramics, basketry, huts
  – Different mode of life: villages
  – Different social life: larger groups
  – Different perception of space & time

• From *harvesting* the environment to *investing* in it. Why?
  – Mobility no longer the way to meet challenges
  – Old system was adapted, could have continued
  – Change in conceptual toolkit evolved during Pleistocene

• Is climate driver or enabler?
Neolithic technologies

Mergarh neolithic village, Iran

Neolithic ard (reconstructed)

Stonehenge

Neolithic statue, Romania

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How did that change the dynamics?

- Reciprocal relationship to environment and climate
  - Climate can change society and vice versa!
- Growing interventionism in nature
- Sedentary societies try to control environmental risk:
  - Simplify the environment
  - Spatial and technical diversification
- As the system integrates, it is more vulnerable to disturbances
- The emphasis shifts to problem-solving
  - Diversification and specialization
  - Ever larger interactive groups
- The cost is growing social complexity
  - Increasing investment in maintaining society

As groups grow, cohesion becomes a problem...
Stage 4: Bootstrapping process now the limit

• In the simplest terms:
  – More people --> more needs --> more problems --> more brainpower --> more people …

• In not so simple terms:
  – Problem solving structures knowledge --> increases information processing capacity --> allows the cognition of new problems --> creates new knowledge --> more and more people involved in processing information --> population and its aggregation increase

• In the process, major social transformations
The urban way of life

• Urbanization is costly in energy terms
• Need for better problem solving is the driver, bringing more and more people in more direct contact
• Dynamical structure organizes the environment in order to draw energy from it:
  – Outbound flow: organization;
  – Inbound flow: energy
• To keep the flows going, innovation in center is essential
  – Innovation needs/attracts people
  – Innovation requires many cognitive dimensions, thrives in towns, comes to drive urbanization
The first ‘cities’

Uruk (reconstruction)

Hamukar

Caral, Peru
Cities emerge in clusters, invent accounts, writing, law, etc.
The Imperial way of life

• Energy ever more of a constraint
  – Dynamical structures to cross societies, languages, cultures …
  – Not possible unless they can use pre-collected energy (treasure)
• Roman Empire as an example
  – Grew on the back of centuries of ‘leaked’ organization to Mediterranean periphery
• From ‘power to’ to ‘power over’:
  – Formal institutions and their roles
    • From conflict resolution to resource and people management
  – Roads and communication
Empires as flow structures

- Energy and matter (resources) are gathered to meet human needs
  - To do so, the environment is organized
- Societies are flow structures that exchange information (organization) for resources
  - Channels emerge through recursive interaction between people
  - Interaction aligns people’s ideas, language and culture
  - It does so self-referentially – shapes the environment
- Center-periphery structure driven by invention and innovation
  - Value gradient inversely proportional to innovation gradient
Growth of the Roman Empire 44 BC-AD 117

As it grows ...

roads keep it together
Growth of the Roman Empire

• Enabled by ‘leaked’ organization beyond its borders
• Rapid expansion cannibalizing collected resources, incorporating organization by aligning ideas and institutions
• Flow structure functioned until there was nothing more to conquer
• Then internal investment to exploit environment
Collapse of the Roman Empire

• C. AD 250 the invention/value creation engine at the core stalled
  – Organization became too costly in resources
  – Devaluation of coinage

• Spatial gradients levelled out
  – More difficult to get enough resources to the core
  – Coherence is lost, independent societies emerge at margins
Imperial collapse as energy collapse

• Not really a collapse in population terms, only in organization terms
  – Splitting the Empire into four parts
  – Armies lose control at edges: incursions

• Net annual productivity too low to carry overheads
  – Increases in taxation
  – Inflation

• Loss of attractivity - people fall back on local solutions
  – Latifundia become local powers
  – Nimes loses control over water
  – Centers at the edges of the Empire (Trier)
The trajectory of the
west 1000-1800:
measures

- Relative population increases and decreases.
- Area that a system can coherently organize;
- Trade proxy for information potential between center and periphery, ‘footprint’;
- Density and extent of transport and communication systems
- Wealth gradient proxy of innovation and value gradients;
- Innovativeness of towns, regions and periods.
AD 700-1000: Dark Ages

- High entropy, low alignedness
- Very limited extent of flow structures: little trade
- Huge loss of information in crafts, technology and industry
- Abandonment of infrastructure
- Demographic drop
- Local survival strategies
AD 1000-1200: First stirrings

- Oscillation between different small systems
  - Cohesion alternates with entropy
- New spatial structure from bottom up (Duby 1953)
- Old (Roman) and new (Hanseatic league) towns isolated
- Competition for access of local resources leads to new (feudal) social/hierarchical structure
  - Local emergence of upper class (12th cty Renaissance)
- Small surplus enables local armies
AD 1200-1400: Renaissance

• Durable link between S and N European centers
  – N Italy – Champagne – Low Countries – Briatain – Hanseatic League

• Black Death in the 14th C. – population shifts
  – Increased urban aggregation and wealth
  – Major cultural and social shifts

• Beginnings of the Italian Renaissance.
  – Rapid increase in information-processing gradient between N. Italian cities and the rest of the continent

• ‘Top of the heap’ limited to towns
  more diverse resources and more effective information processing connecting wider areas
AD 1400-1600: Birth of the modern World System

• Continent-wide transition from rural barter to monetized urban economy
  – Hierarchical rural structures replaced by market-based, heterarchical ones
    • do not optimize behavior; more flexible
    • link much larger number of people in networks with nodes

• Trade & commerce expand across political entities

• Heyday of city power and urban immigration

• Exploration of the rest of the world: new downstream information processing areas
  – Steepest information-processing and value gradients
AD 1600-1800: territorial states and trading empires

• Merging of political and economic power
  – Cities and rulers eventually come to mixed hierarchical- heterarchical systems
  – Taxes exchanged against security; territorialization

• Focus on intercontinental resource acquisition
  – Leveling off of value gradient initially compensated by acquisition of new territories + products
  – Later this leads to either independence of some colonies (US) or exploited colonies under military control (India)

• Increase in industrial base of European nations, including more people in production
The Industrial revolution c. AD 1800

- All earlier societies limited by energy needs
  - Colonial Empires
- Around 1800 energy problem (temporarily) solved with fossil energy
- Innovation becomes endemic, supply-driven
- Western society dependent on it to continue creating value and attracting people into its system

Way free to harness 10,000 watts/person, invested in society and material culture
The underlying pattern

• Once the biological constraints to innovation have been overcome we see:
  – Innovations leading to challenges, leading to innovations
  – Humans overcoming major hurdles

• What drives that dynamic?
  – A tangled hierarchy between two perceptions of the relationship between society and environment
  – Leading to more and more human intervention in the environment unless constrained externally
The perception cycle

Opening a category ...

... and closing it

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More is different

The cohesion of nature, its unknown aspects, its strangeness and force are amplified.

The confusion and the handicaps of humanity are accentuated.

Change is attributed to nature, and people have no other choice but to adapt to nature.

Natural changes tend to be viewed as dangerous, because they are beyond the control of humanity.

Humanity is passive in a natural environment which is active and aggressive.

Humanity is compared to nature.

Nature is compared to humanity.

Cohesion and strength are accentuated in humanity, in a natural environment that is passive.

Humanity tends to be viewed as the source of all change, people as creating their environment.

Natural changes seem more controllable and lose their dangerous appearance.

The cohesion and strength of nature is diminished, its known aspects emphasized.

Humanity is viewed as the source of all change, people as creating their environment.
… and their interaction

- “Milieu” and “environnement” perspectives are complementary and interact

- Natural dangers are exaggerated, those of human intervention systematically undervalued.
  - Encourages society to intervene in its natural environment
  - Gives the impression that society’s actions reduce risks

- In reality, society reduces by its actions the predictability of natural phenomena.
  - Society loses control: the more it transforms its surroundings, the less it understands them.

- This seems to be an irreversible tendency!
Disturbance-dependency

• Complex ecological systems consist of hierarchies of dynamics on multiple spatio-temporal scales
• Faster dynamics easily take control of slower dynamics, but not vice-versa
• Ultimately, a role reversal between the two:
  – “human” dynamics (rapid, but initially without much impact) control the (slower) “natural” dynamics, that are more encompassing
• Landscapes “disturbance-dependent”.
• Irreversible tendency related to the perception cycle
Risk spectrum shifts

• Any society’s risk spectrum shifts over time with respect to its environment.
  – Perception over-emphasizes frequent risks, leading to action
  – Action introduces new risks, both short and long-term.
  – Long-term socio-environmental interaction shifts the risk spectrum towards the long-term.
  – Eventually, society will meet a “risk barrier” by analogy to a “sound-barrier”. That may just be a bit too much …

• Another irreversibility related to the perception cycle!
Unintended consequences

• Human perception has limits due to STWM
  – Usually, we consider 6-8 dimensions of a phenomenon
  – Human interventions in the environment are based on a simplified vision of the world
• Our interventions touch the (infinitely) many dimensions of environmental dynamics
  – They therefore always create more (unanticipated) problems than they solve
• The more we think we know, the less we know
Fragmentation of our understanding

- Due to increase in group size, shorter interactions, narrower concepts
- Reductionist science focuses on origins rather than emergence, creativity ‘out of bounds’
- Unanticipated consequences overwhelm us
- Crisis: ‘temporary incapacity of society to process the information necessary to deal with the external and internal dynamics it is engaged in’.
- What can we do?
Proximate causes

- Path-dependency due to under-determination of theories by observations
- Fragmentation of our world view (language)
- Scientific reductionism
  - Ex-post vs. ex-ante perspective
- Proliferation of innovation and objects
- GDP as principal measure of societal health
- New feedback loops (medicine-demography)
- Education has not kept pace (cf. Reinicke)
- Globalization
The Information revolution as opportunity

• We have the means to control matter, energy and information

• To shape our future, we must
  – Understand the innovation process
  – Decide the (sustainable) future we want
  – Battle (with) ourselves to achieve change

• Sustainability firmly within the social sciences
  – The innovation debate as an essential component
  – Complex systems approach because of increase in dimensionality
  – Computer science and modeling essential tools

• Redefine our social structures and institutions
Transforming our thinking

• Lessons for the future!
  – Argue from the simple to the complex
• Counter path-dependency due to over-determination of theories by past experience
  – Massive data collection
• Enhance the number of dimensions
  – Use ICT in the inverse sense
• Compare choices made with options ignored
  – Anticipate more consequences of decisions made
• Improve multidimensional skills & communication