Chapter 10 - Complex Systems and Self-Organization

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Complex systems

- Defining characteristics of complex systems:
  - Large number of components. Examples:
    - The number of neurons in human brain, estimated to be 80 -120 billion.
    - The space shuttle: 2.5 million parts, 230 miles of wire, 1,040 valves and 1,440 circuit breakers.
    - Modern microprocessors: 4.3 million for the Tahiti GPU of AMD.
    - The number of servers used by Amazon EC2 > 0.5 million.
  - A very large number of interaction channels among the components.
  - Complex interaction with the environment.
  - Lack of symmetry and regularity.

Quantifying complexity

- Thermodynamic entropy, von Neumann entropy, and Shannon entropy are related to the number of states of a system, thus they reflect to some extent the system complexity.
- Relative predictive efficiency, e=E/C with E the excess entropy and C the statistical complexity. The excess entropy, E, measures the complexity of the stochastic process and can be regarded as the fraction of historical information about the process that allows us to predict the future behavior of the process. The statistical complexity, C, reflects the size of the model of the system at a certain level of abstraction.
- The Kolmogorov complexity $K_V(s)$ of the string *s* with respect to the universal computer *V* is defined as the minimal length over all programs $Prog_V$ that print *s* and halt. Kolmogorov complexity is to provide the shortest possible description of any object or phenomena.

Emergence

- Emergence→ lacks a clear and widely accepted definition; it is generally understood as a property of a system that is not predictable from the properties of individual system components.
- Manifestations of emergence → physical phenomena which do not manifest themselves at microscopic scales but occur at macroscopic scale, e.g., the temperature is a manifestation of the microscopic behavior of large ensembles of particles.
- Emergence could be critical for complex systems such as the financial systems, the air-traffic system, and the power grid.
  - A 600 points drop in a short period of time of the Dow Jones Industrial Average is a manifestation of emergence. The cause - the interactions of trading systems developed independently and owned by organizations which work together, but their actions are motivated by self interest.
  - The failures of the power grid can also be attributed to emergence; during the first few hours of the event the cause of the failure could not be identified due to the large number of independent systems involved.

Self-organization

- Informally, self-organization means synergetic activities of elements when no single element acts as a coordinator and the global patterns of behavior are distributed.
- The intuitive meaning of self-organization is captured by the observation of Alan Turing: *global order can arise from local interactions.*
- Self-organization is prevalent in nature:
  - In chemistry the process is responsible for molecular self-assembly, for self-assembly of monolayers, for the formation of liquid and colloidal crystals.
  - Spontaneous folding of proteins and other biomacromolecules.
  - The formation of lipid bilayer membranes.
  - The flocking behavior of different species.
  - The creation of structures by social animals.
- Self-organization was proposed for the organization of different types of computing and communication systems, including sensor networks, for space exploration, or even for economical systems.

Self-organization and complexity

Simple systems; no self-organization	Complex systems; self-organization
Mostly linear	Non-linear
Close to equilibrium	Far from equilibrium
Tractable at component level	Intractable at component level
One or few scales of organization	Many scales of organization
Similar patterns at different scales	Different patterns at different scales
Do not require a long history	Require a long history
Simple emergence	Complex emergence
Unaffected by phase transitions	Affected by phase transitions
Limited scalability	Scale-free

Scalability – an attribute of self-organization

- The ability of the system to grow without affecting its global function.
- Complex systems encountered in nature or man-made enjoy a scale-free organization.
- A scale-free organization is reflected by the network model of the system, a random graph with vertices representing the entities and the links representing the relationships among them. In a scale-free organization the probability *P(m)* that a vertice interacts with *m* other vertices decays as a power law, $P(m) \sim m^{-k}$ with *k* a real number, regardless of the type and function of the system, the identity of its constituents and the relationships between them. Examples:
  - The collaborative graph of movie actors where links are present if two actors were ever cast in the same movie: k= 2.5.
  - The power grid of the Western US has some 5000 vertices representing power generating stations: k = 4.
  - The World Wide Web: k = 2.1.
  - The citation of scientific papers: k = 3.

Scaling

- Scaling has other dimensions than just the number of components: the space plays an important role, the communication latency is small when the component systems are clustered together within a small area and allows us to implement efficient algorithms for global decision making, e.g., consensus algorithms.
- Societal scaling means that a service is used by a very large segment of population and/or is a critical element of the infrastructure. There is no better example to illustrate how societal scaling affects the system complexity than communication supported by the Internet. The infrastructure supporting the service must be highly available. A consequence of redundancy and of the measures to maintain consistency is increased system complexity.

Phase transitions

- The transformation, often discontinuous, of a system from one phase/state to another, as a result of a change in the environment.
  - Freezing → transition from liquid to solid and its reverse, melting.
  - Deposition → transition from gas to solid and its reverse, sublimation.
  - Ionization → transition from gas to plasma and its reverse, recombination.
- Phase transitions can occur in computing and communication systems due to avalanche phenomena, when the process designed to eliminate the cause of an undesirable behavior leads to a further deterioration of the systems state.
  - Thrashing due to competition among several memory-intensive processes which lead to excessive page faults.
  - Acute congestion which can cause a total collapse of a network; the routers start dropping packets and, unless congestion avoidance and congestion control means are in place and operate effectively, the load increases as senders retransmit packets and the congestion increases.
  - To prevent such phenomena some form of negative feedback has to be built into the system.

Composability bounds

- Nature creates complex systems from simple components. For example, a vast variety of proteins are linear chains assembled from the twenty one amino acids, the building blocks of proteins.
- The limits of composability can be reached because new physical phenomena could affect the system when the physical size of the individual components changes. Even the most modern solid-state fabrication facilities cannot produce chips with consistent properties. The percentage of defective or substandard chip has been constantly increasing as the components have become smaller and smaller.
- There are physical bounds for the composition of analog systems; noise accumulation, heat dissipation, cross-talk, the interference of signals on multiple communication channels, and several other factors limit the number of components of an analog system.
- Digital systems have more distant bounds, but composability is still limited by physical laws.

The role of the software

- There are virtually no bounds on composition of digital computing and communication systems controlled by software. The software is the ingredient which pushes the composability bounds and liberates computer and communication system from the limits imposed by physical laws.
  - The Internet is a network of networks and a prime example of composability with distant bounds.
  - Computer clouds are another example. A cloud is composed of a very large number of servers and interconnects, each server is made up of multiple processors, and each processor has multiple cores.

Modularity

- Has been used extensively since the industrial revolution for building every imaginable product.
- Can reduce cost for the manufacturer and for the consumers. The same module may be used in multiple products; to repair a defective product a consumer only replace the module causing the malfunction rather than the entire product.
- Encourages specialization, as individual modules can be developed by experts with deep understanding of a particular field. It also supports innovation, it allows a module to be replaced with a better one, without affecting the rest of the system.

Layering and hierarchy

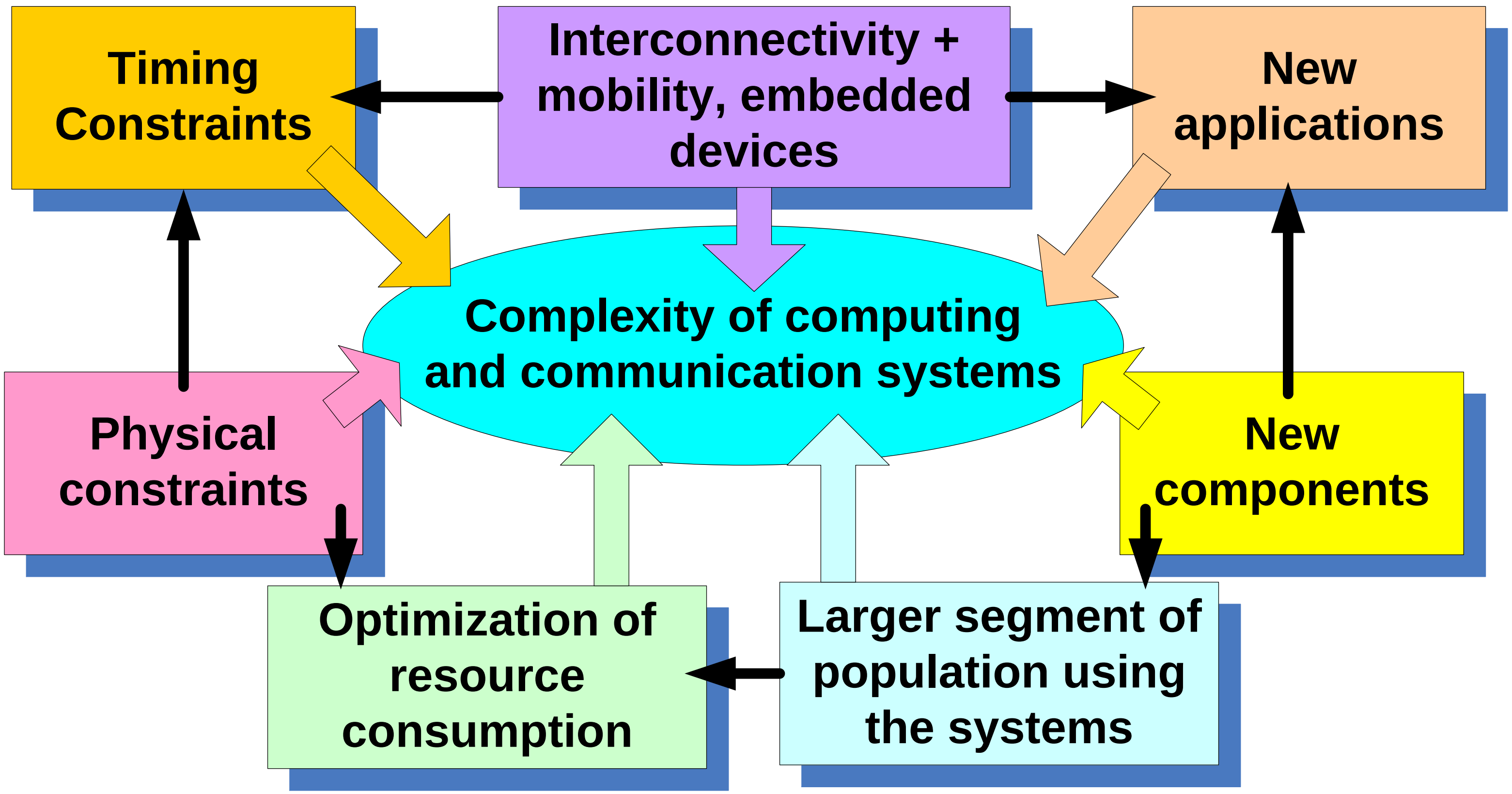
- Layering demands modularity as each layer fulfills a well-defined function, but the communication patterns in case of layering are more restrictive.
- A layer is expected to communicate only with the adjacent ones.
- This restriction, the limitation of communication patterns, clearly reduces the complexity of the system and makes it easier to understand its behavior.
- Layering helps us dealing with complicated problems when we have to separate concerns that prevent us from making optimal design decisions. To do so, we define layers that address each concern and design the clear interfaces between the layers.
- Layering could prevent some optimizations; for example, cross-layer communication could allow wireless applications to take advantage of information available at the Media Access Control (MAC) sub-layer of the data link layer.

Complexity of computing and communication systems

- The behavior of the systems is controlled by phenomena that occur at multiple scales/levels. As levels form or disintegrate, phase transitions and/or chaotic phenomena may occur.
- Systems have no predefined bottom level; it is never known when a lower level phenomena will affect how the system works.
- Abstractions of the system useful for a particular aspect of the design may have unwanted consequences at another level.
- Systems are entangled with their environment. A system depends on its environment for its persistence, therefore, it is far from equilibrium. The environment is man-made and the selection required by the evolution can either result in innovation, or generate unintended consequences, or both.
- Systems are expected to function simultaneously as individual systems and as groups of systems (systems of systems).
- Typically, computing and communication systems are both deployed and under development at the same time.

Factors affecting the complexity of CCS

- The rapid pace of technological developments and the availability of relatively cheap and efficient new system components such as multi-core processors, sensors, retina displays, and high-density storage devices.
- The development of new applications which take advantage of the new technological developments.
- The ubiquitous use of the systems in virtually every area of human endeavor which, in turn, demands a faster pace for hardware and software development.
- The need for interconnectivity and the support for mobility.
- The need to optimize the resource consumption.
- The constraints imposed by the laws of physics, such as heat dissipation and finite speed of light.



Factors contributing to the complexity of modern computing and communication systems. The slim black arrow show a causality relation between individual factors; for example, physical constraints demand optimization of resource consumption.

System of systems (SoS)

- SoS → collections of independent systems with limited interactions.
  - The individual components of a SoS are independent and can be operated alone, disconnected from the other system components.
  - The components enjoy managerial independence and, in fact, do operate independently for some periods of time.
  - The system of systems continually evolves in time as new functions are added while others are removed.
  - The system is able to perform functions that cannot be performed by any of its components alone; in other words, it has an emergent behavior.
  - The components exchange only information, thus, they can be geographically distributed over a large area; as the performance of interconnection networks improves, this geographic spread becomes less and less noticeable and does not affect the function or the performance of the SoS. This is in contrast with systems which exchange mass or energy, when the distance between components plays a significant role.