Overcoming Software Fragility with Interacting Feedback Loops and Reversible Phase Transitions

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BCS 08 – Visions of Computer Science

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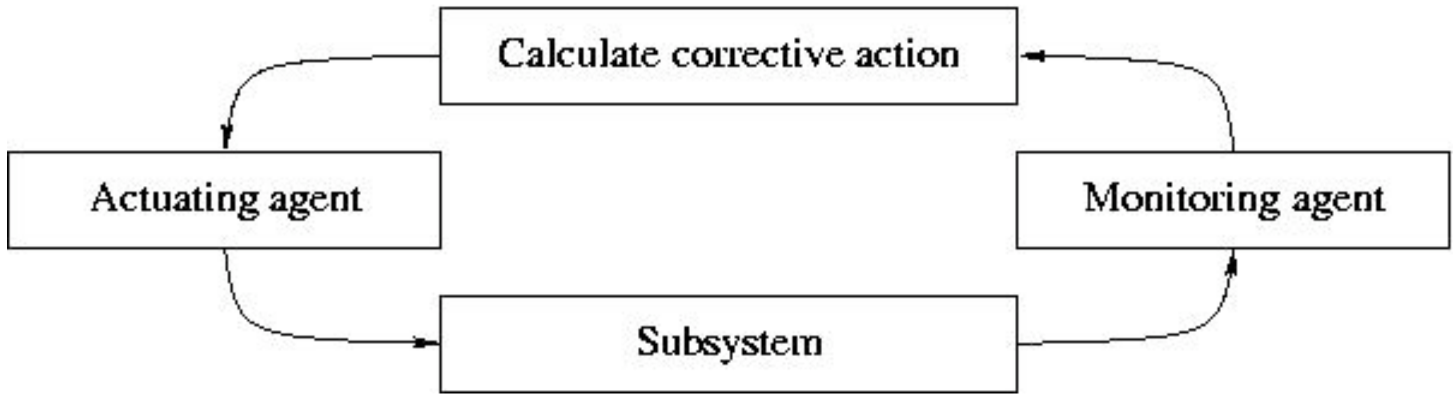
Overview

- Motivation for interacting feedback loops
  - Example from Norbert Wiener
  - Human respiratory system
  - Software example: TCP
- Structured overlay networks (THE ADVENTURES OF SELFMAN project)
  - We are using overlay networks for distributed applications
  - Relaxed ring: handles imperfect failure detection
  - Merge algorithm: handles network partitioning
- Physical analogy
  - Our practical structured overlay network shows phases
  - Robust software should have reversible phase transitions

Interacting feedback loops

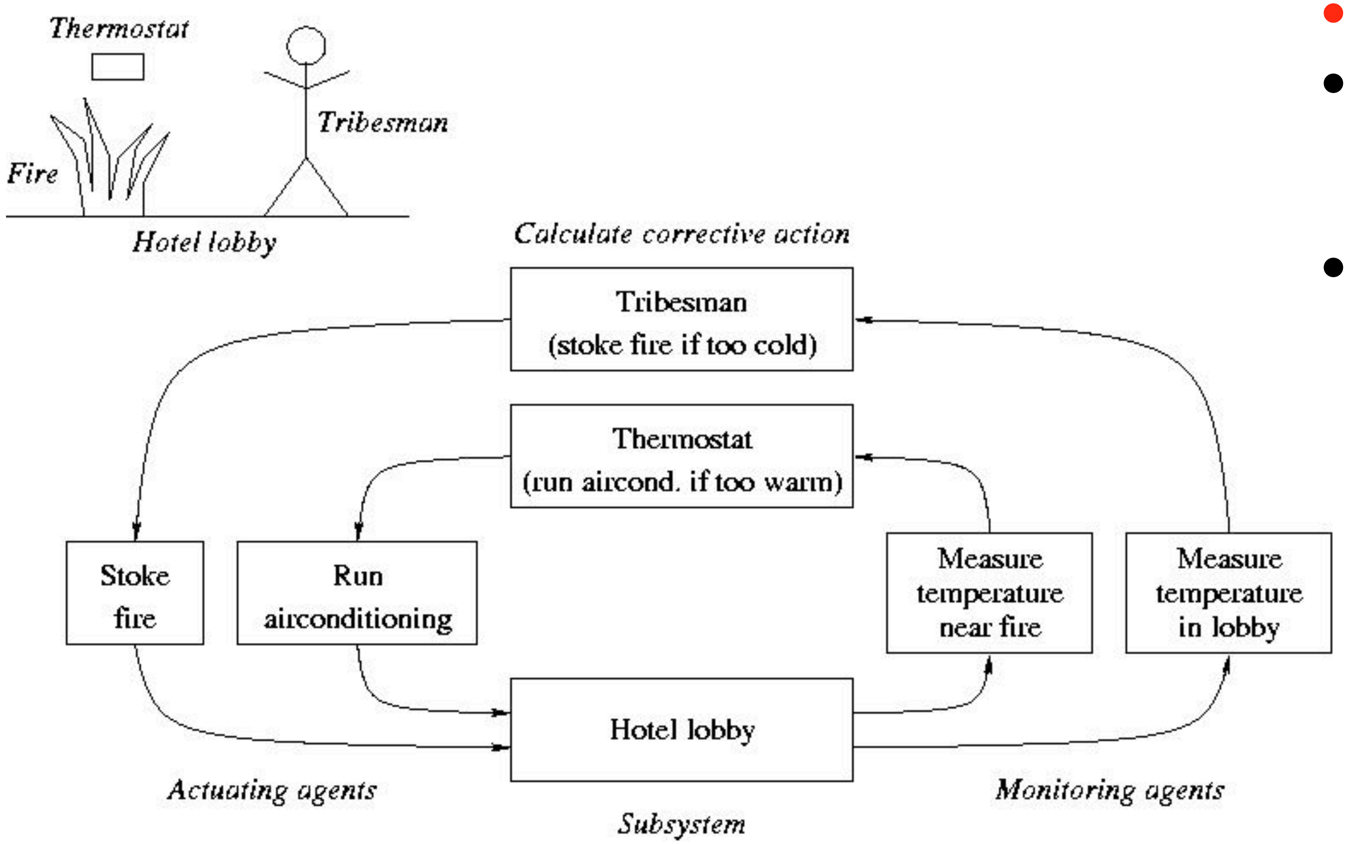
Feedback loops



- A feedback loop consists of three elements that interact continuously with a subsystem: a monitoring agent, a correcting agent, and an actuating agent
  - The elements and the subsystem are concurrent components interacting through asynchronous message passing
  - The correcting agent has an abstract model of the system and a goal
  - The model does not have to be complete but it has to be correct
- Example: transaction manager using concurrency control
  - monitor = resource request, actuator = resource grant/refusal, corrector = model of who has exclusive access to what resources

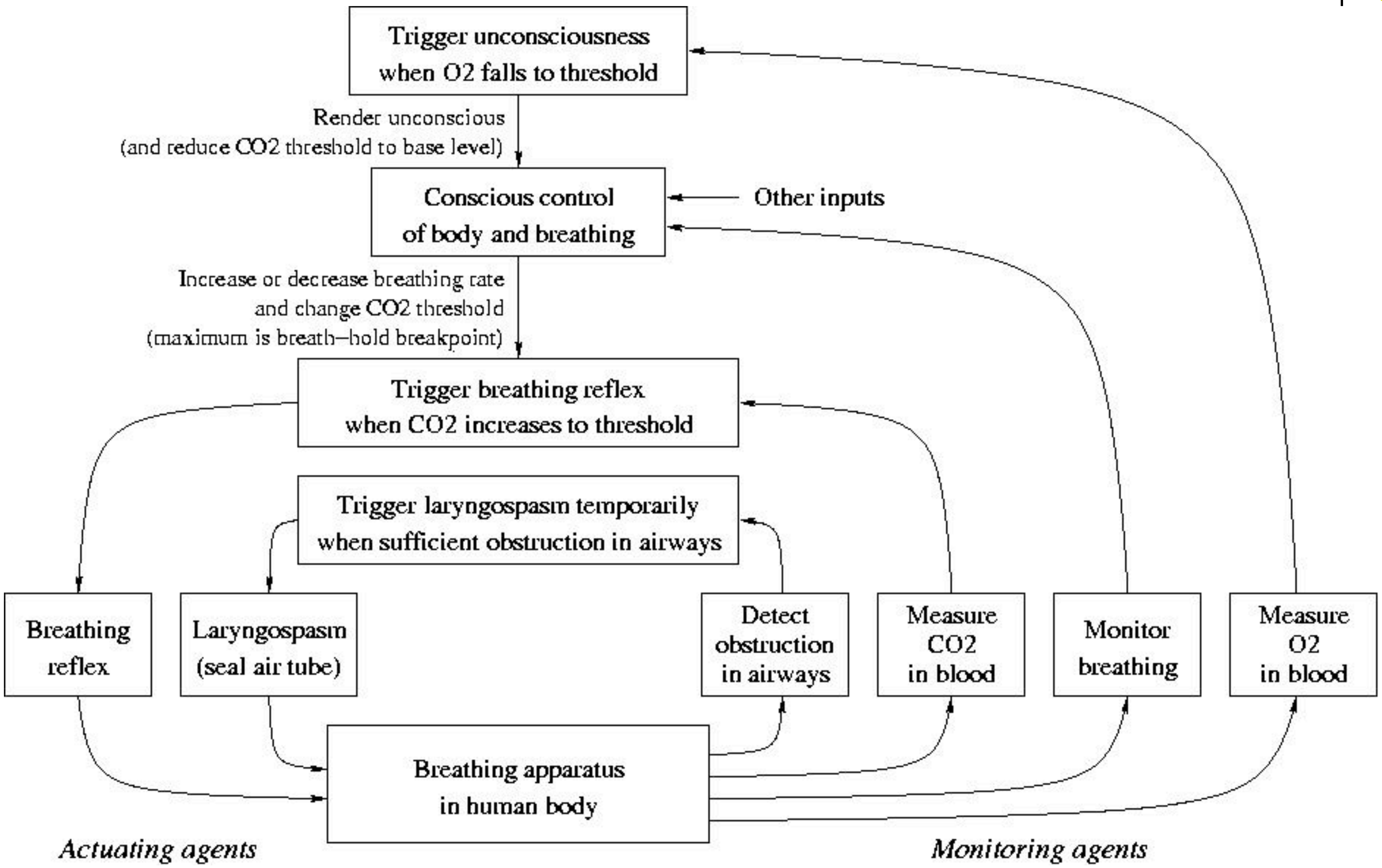
Example from Wiener (1948)

- A system with two loops interacting through a common subsystem



- This is unstable!
- Wiener leaves the fix as homework for the reader
- One possible solution: outer loop (tribesman) controls the other by simply adjusting the thermostat
  - One loop controls the other

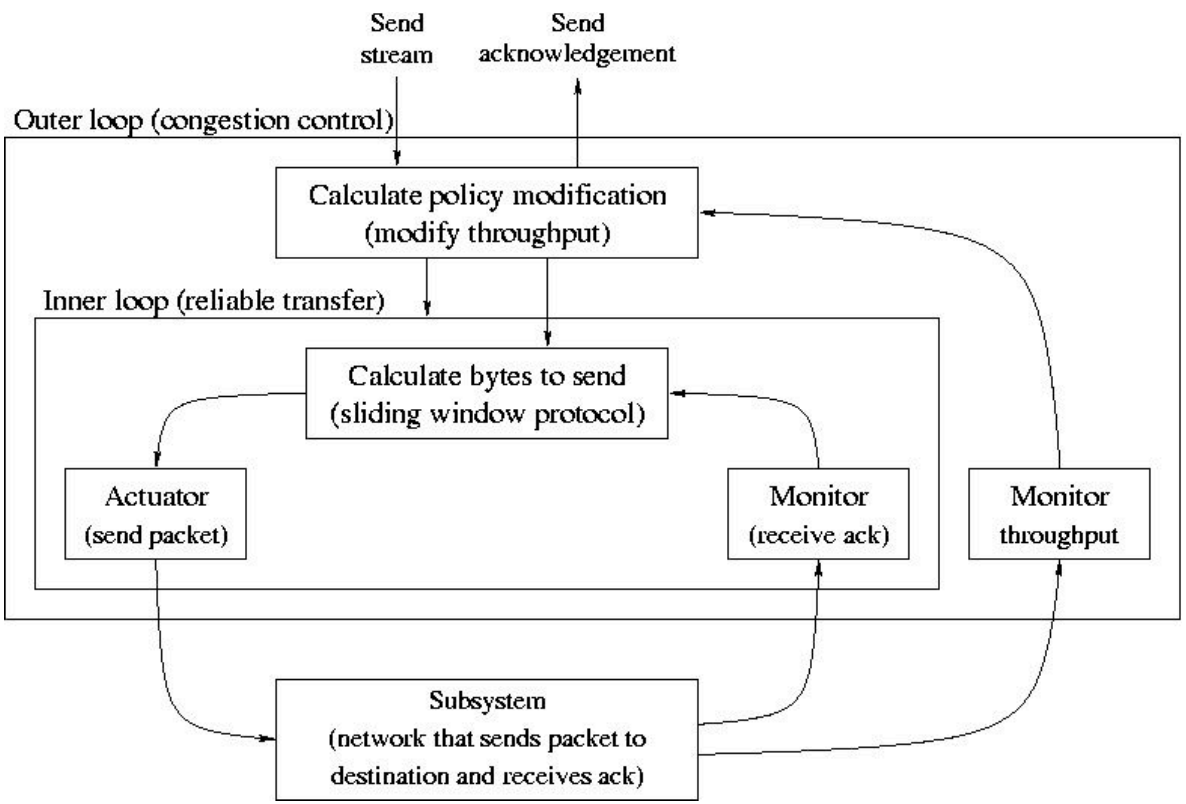
Human respiratory system



Discussion of respiratory system

- Four interacting feedback loops: two inner loops (breathing reflex and laryngospasm), a loop controlling the breathing reflex (conscious control), and an outer loop controlling the conscious control (falling unconscious)
  - This design is derived from a precise textual medical description (if you believe Wikipedia : entry "Drowning" from 2006)
- Holding your breath can have two effects
  - Breath-hold threshold is reached first and breathing reflex happens
  - O_2 threshold is reached first and you fall unconscious, which reestablishes the normal breathing reflex
- Some plausible design rules inferred from this system
  - Common design pattern: one loop controlling another
  - Conscious control is sandwiched in between two simpler loops: the breathing reflex provides abstraction (consciousness does not have to understand details of breathing) and falling unconscious provides protection against instability

Software example: TCP



- This example shows a reliable byte stream protocol with congestion control (a variant of TCP)
  - This diagram is for the sending side
- The congestion control loop manages the reliable transfer loop
  - By changing the sliding window's buffer size
- Again, an essential pattern is one loop controlling another

Structured overlay networks (“peer-to-peer”)

Robust distributed systems with structured overlays

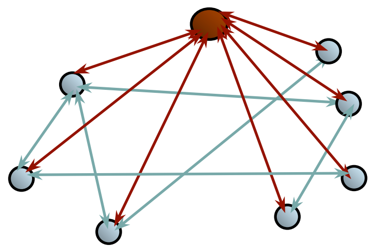
- How can one build robust distributed systems?
  - One approach is to make them decentralized and self-managing
    - No single point of failure, every node can play any role
  - A good example is the structured overlay network, which is an example of a peer-to-peer network with strong self-organizing properties
  - In the SELFMAN project we have built a practical structured overlay network, a transactional storage service on top, and a Distributed Wiki application using this service (*)
- For SELFMAN it is important to make overlay networks practical
  - Coping with imperfect failure detection and network partitioning
  - For imperfect failure detection: the relaxed ring [Mejias *et al* 2008]
  - For network partitioning: the merge algorithm [Shafaat *et al* 2008]
- We then made an observation that led to this paper:
  - Both of these contributions lead to the same physical analogy

THE ADVENTURES OF SELFMAN

(*) First prize in IEEE International Scalable Computing Challenge (SCALE 2008)

Structured overlay networks: inspired by peer-to-peer

- Hybrid (client/server)
  - Napster

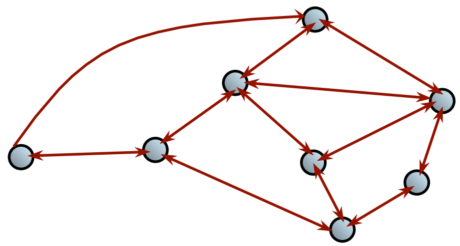


R = *N*-1 (hub)

R = 1 (others)

H = 1

- Unstructured overlay
  - Gnutella, Kazaa, Morpheus, Freenet, …
  - Uses flooding

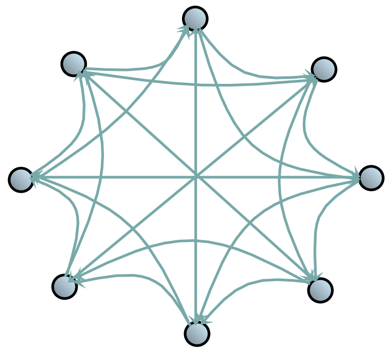


R = ? (variable)

H = 1…7

(but no guarantee)

- Structured overlay
  - Exponential network with ring structure
  - DHT (Distributed Hash Table), e.g., Chord, DKS, P2PS



R = log *N*

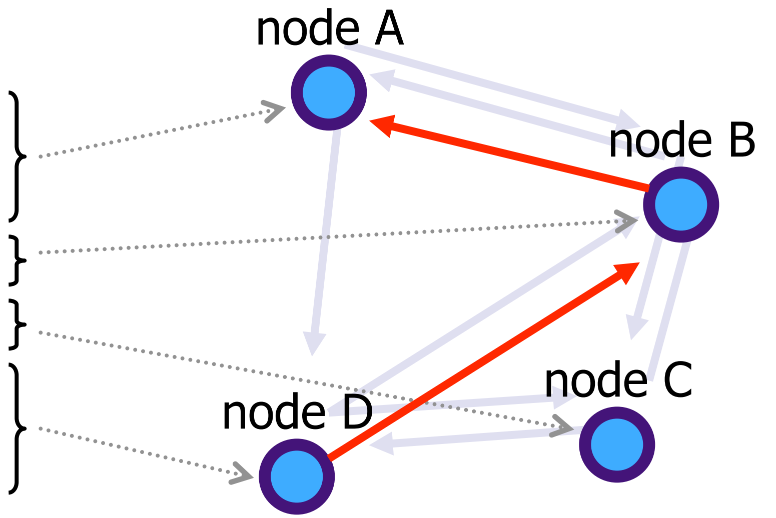
H = log *N*

(with guarantee)

Distributed Hash Tables

- Dynamic distribution of a *hash table* onto a set of cooperating nodes

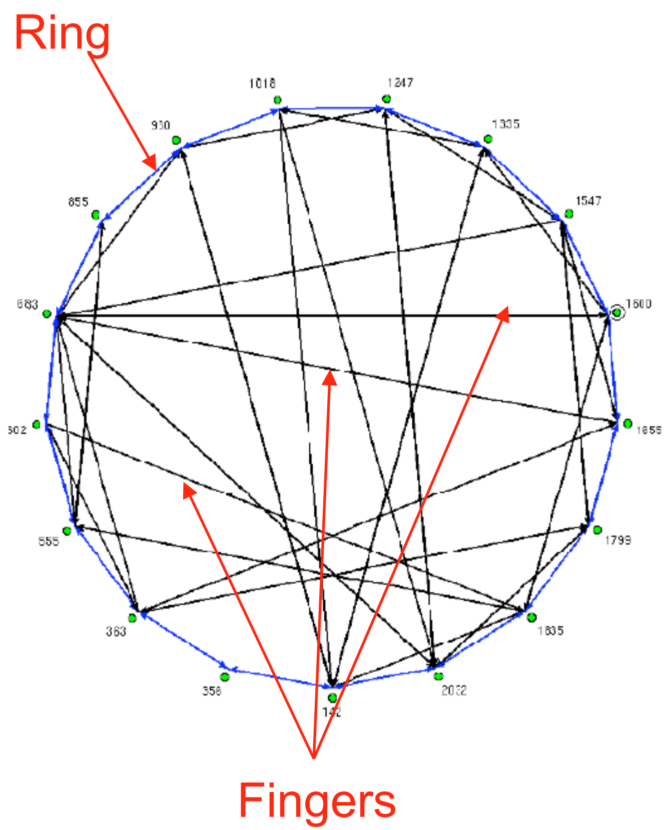
Key	Value
1	Algorithms
9	Routing
11	DS
12	Peer-to-Peer
21	Networks
22	Grids



- Basic service: lookup operation
  - Key resolution from any node
- Each node has a routing table
  - Pointers to some other nodes (called "fingers")
  - Typically, a constant or a logarithmic number of pointers

→Node D : lookup(9)

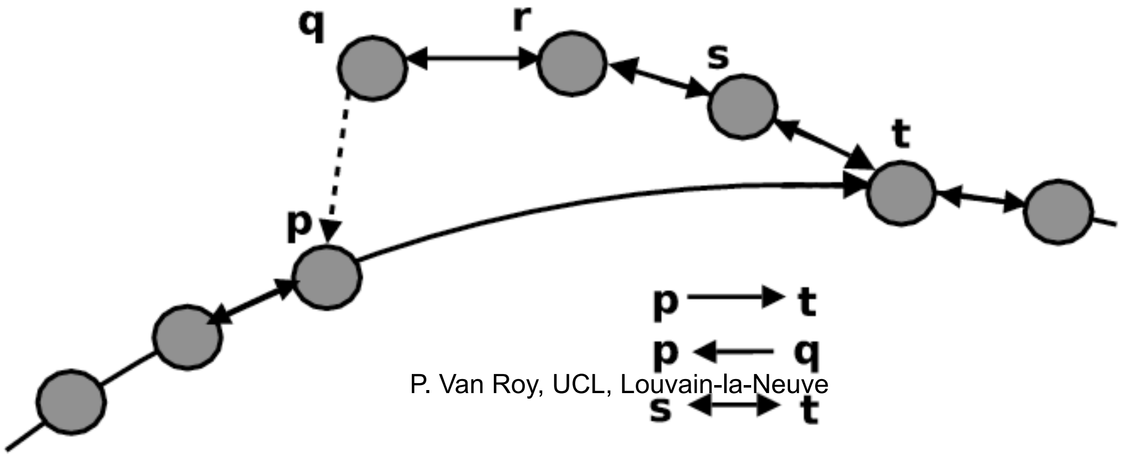
Ring structure



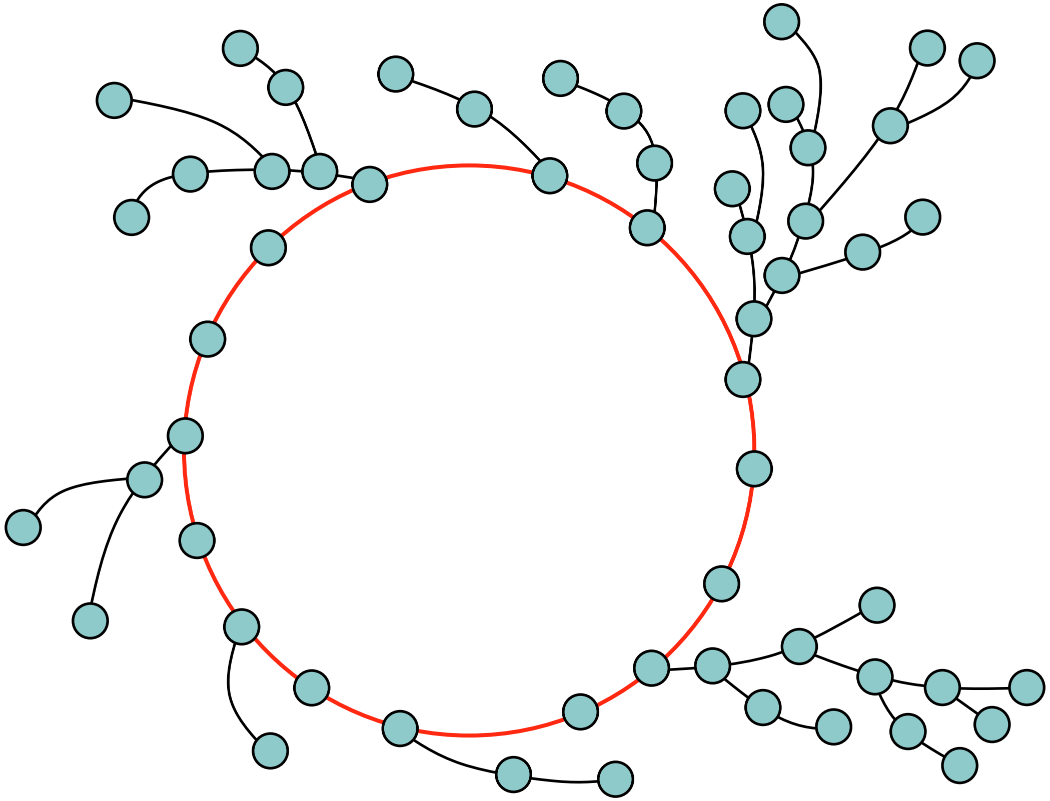
- Structured overlay networks are based on a ring structure
  - By far the most popular structure, it has many variants and has been extensively studied
- Self organization is done at two levels:
  - The ring ensures connectivity: it must always exist despite node joins, leaves, and failures
  - The fingers provide efficient routing: they can be temporarily in an inconsistent state

The relaxed ring

- False failure suspicions are common on the Internet
  - We do not want to eject the node from the ring when this happens
- The relaxed ring solves this by doing ring maintenance in asynchronous fashion [Mejias *et al* 2008]
  - Nodes communicate through message passing
  - For a join, instead of one step involving 3 peers (as in Chord or DKS), we have two steps each with 2 peers → we do not need locking or a periodic stabilization algorithm
- Invariant: Every peer is in the same ring as its successor



Example of a relaxed ring



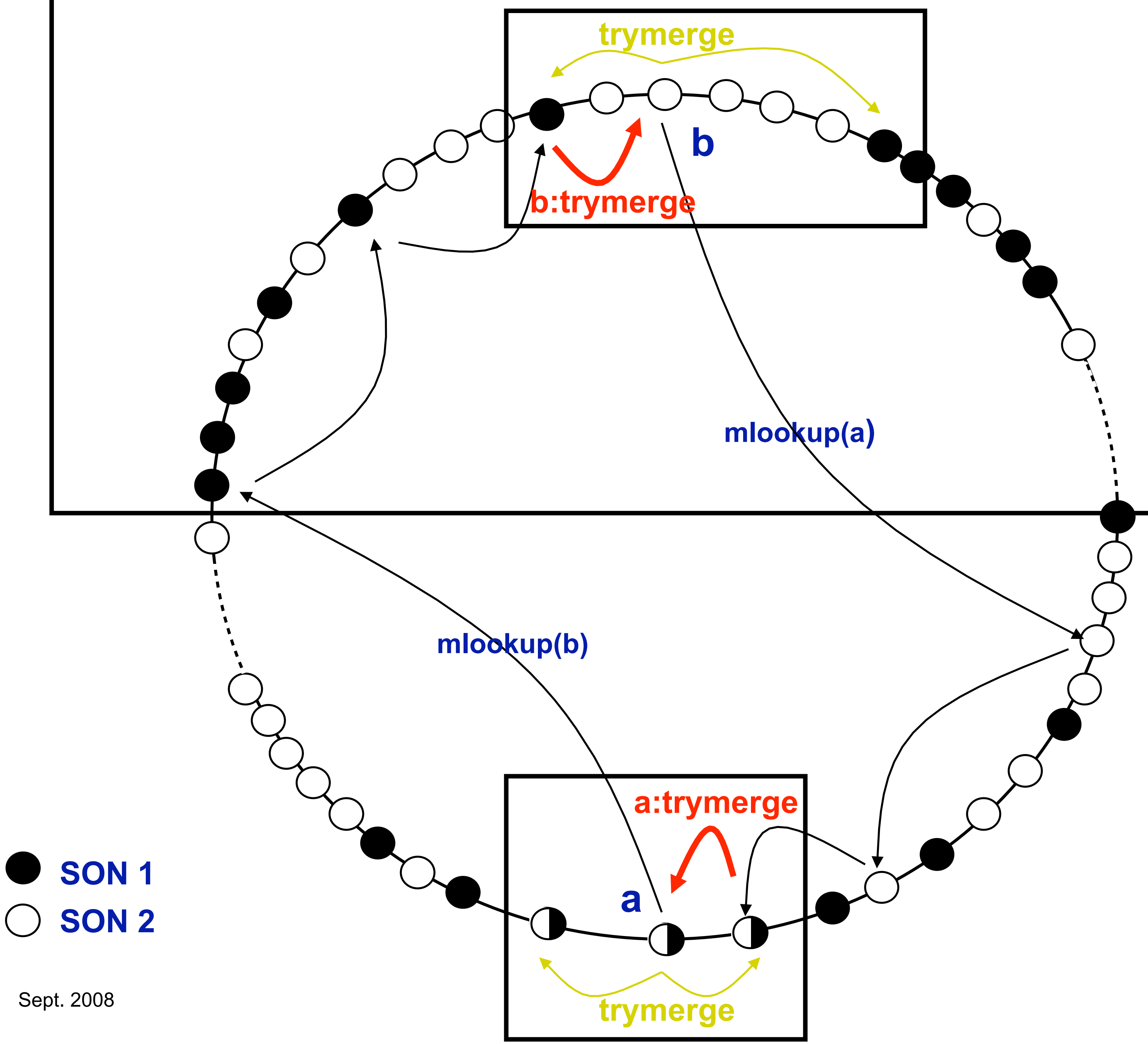
- It looks like a ring with "bushes" sticking out
- The bushes appear only if there are failure suspicions
  - "Bushiness" increases with failure suspicion rate
- There always exists a perfect ring (in red) as a subset of the relaxed ring
- The relaxed ring is always converging toward a perfect ring
  - The bush structure existing at any time depends on the churn (rate of change of the ring, failures/joins) and the failure suspicion rate

The merge algorithm (1)

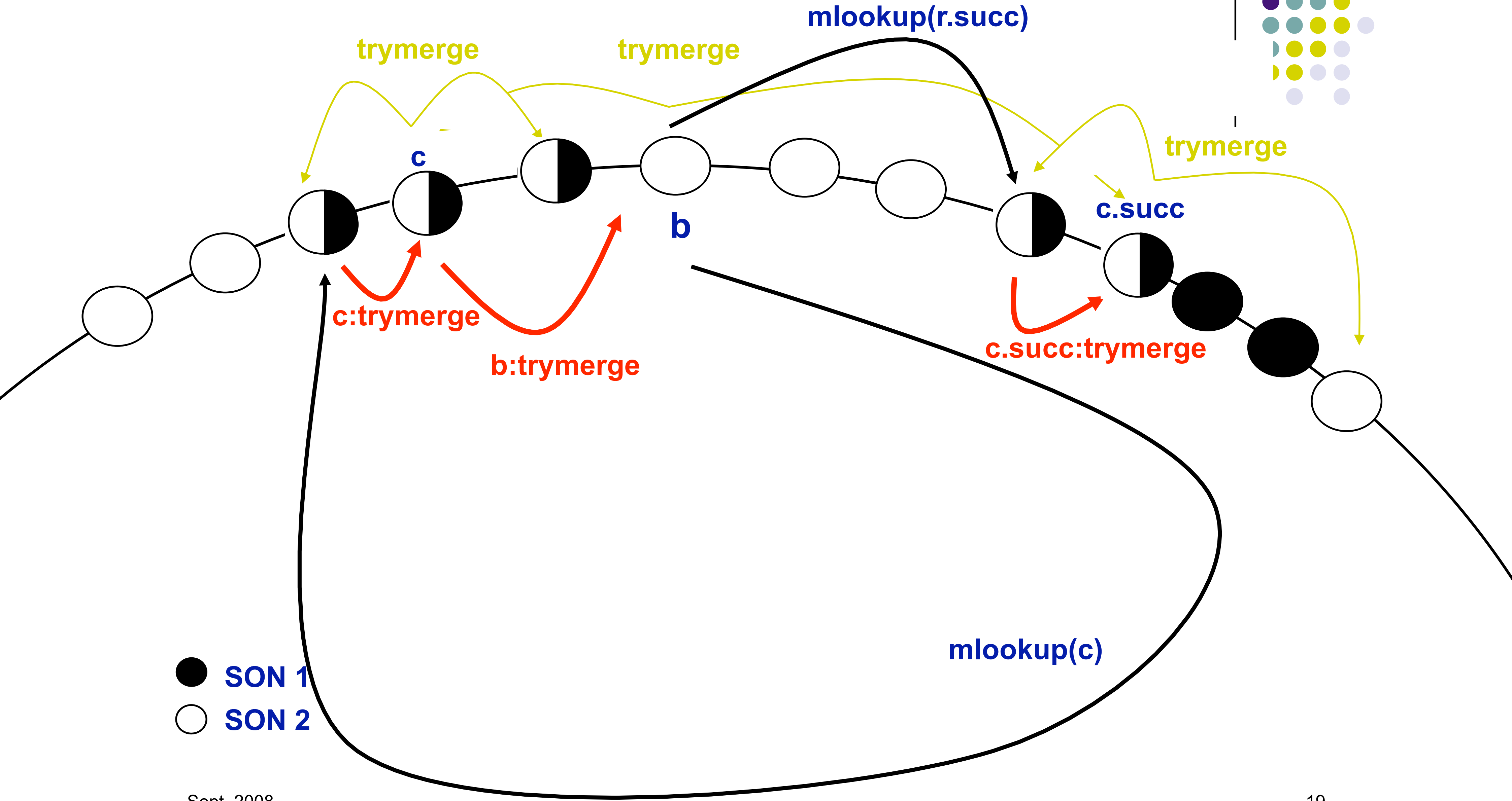
- Network partitioning is a common occurrence in realistic networks (such as the Internet)
  - The nodes are partitioned into several groups, with no communication between groups
- With properly designed ring maintenance, each group continues to work as a single structured overlay network
  - But the groups do not communicate, even when the network partition is removed
- The merge algorithm is designed to merge the groups back into a single overlay network [Shafaat *et al* 2008]
  - Before we designed this algorithm, structured overlay networks would break irreversibly when the network partitioned

The merge algorithm (2)

- The algorithm has two parts
  - Automatic detection of when to merge
    - Each node maintains a passive list of nodes without communication
    - These nodes are pinged periodically
  - Simple ring unification algorithm
    - Assume node *a* detects node *b* on another ring
    - Node a calls mlookup(*b*) to find *b*'s place in the ring
    - When *b* is adjacent, then call trymerge(c_{pred}, c_{succ}) to insert the node
    - Recursive call to mlookup; stops when mlookup to itself
- Optimized versions of the algorithm use gossip to achieve logarithmic time


trymerge
b
b:trymerge
mlookup(a)
mlookup(b)
a:trymerge
a
trymerge
SON 1
SON 2

18

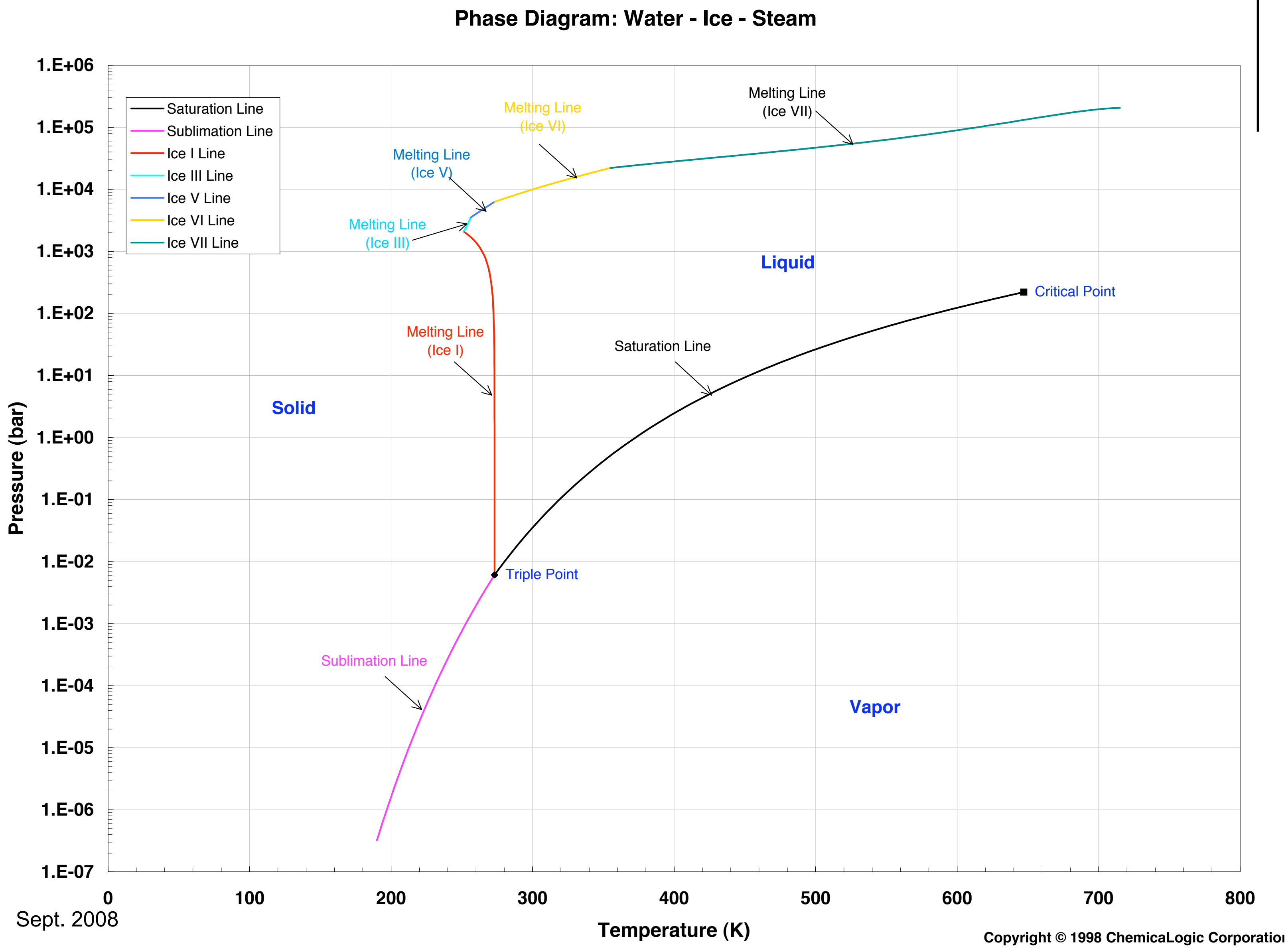

mlookup(r.succ)
trymerge
trymerge
trymerge
c
b
c.succ
c:trymerge
b:trymerge
c.succ:trymerge
mlookup(c)
SON 1
SON 2

Physical analogy

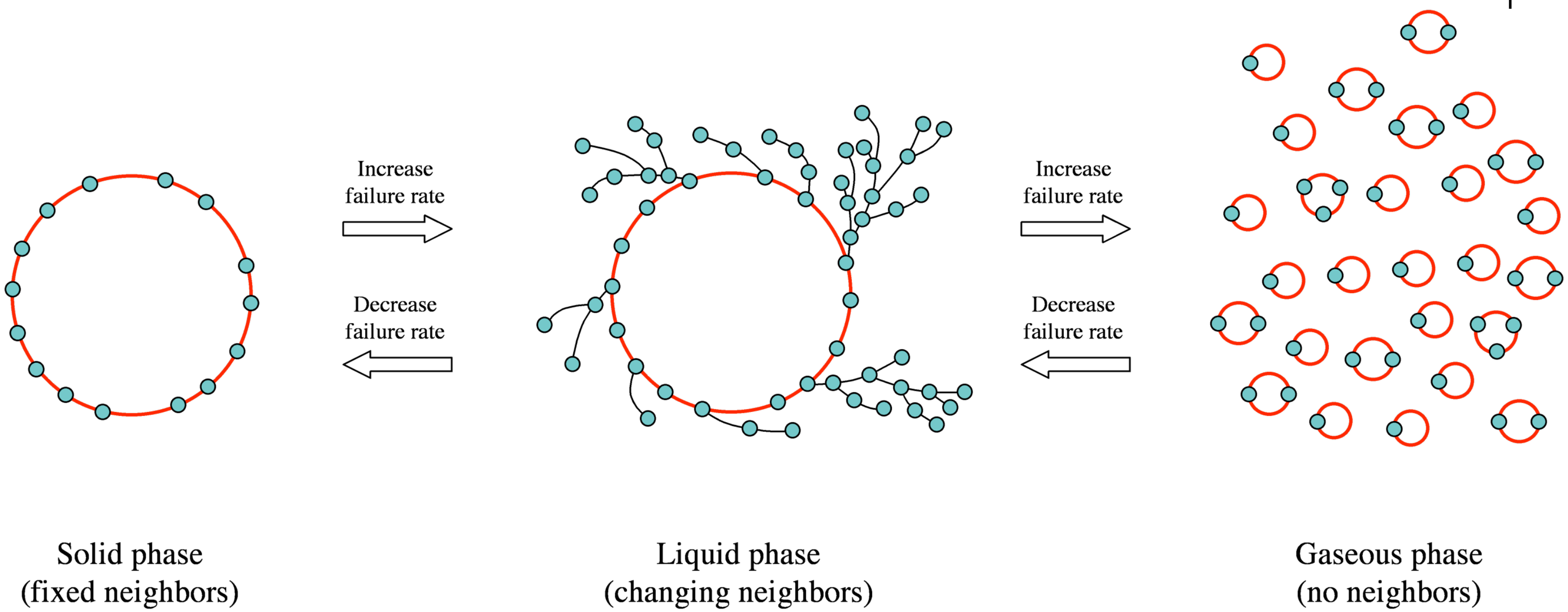
Phase transitions?

- A phase is a set of states of a macroscopic physical system that have relatively uniform chemical composition and physical properties (i.e. density, crystal structure, index of refraction, and so forth).
  - A phase is a region in the parameter space of thermodynamic variables in which the free energy is analytic; between such regions there are abrupt changes in the properties of the system, which correspond to discontinuities in the derivatives of the free energy function.
- Our structured overlay network shows characteristics reminiscent of phases and phase transitions
  - At low failure suspicion rates, the ring is a perfect ring where each node has a fixed set of neighbors (solid phase?)
  - At higher failure suspicion rates, the ring has a bushy structure that is always changing; each node has a varying set of neighbors (liquid phase?)
  - At yet higher failure suspicion rates, the ring degenerates into several disconnected rings, and at highest failure suspicion (failed communication), each node is a ring of size 1 (gaseous phase?)

Water/ice/steam phase diagram



Phases in the relaxed ring



- The relaxed ring has (at least) three phases
- We are studying its behavior to understand how the ring reacts to external parameters (including phase transitions)

Some remarks

- Analytic study of Chord shows three phases with transitions as network delays increase [Krishnamurthy and Ardelius, 2008]
  - Chord is an idealized structured overlay network with simple algorithms
  - Three phases: (1) a region of efficient lookup, (2) a region of inefficient lookup (long fingers are dead), (3) a region of disconnected ring
  - The inefficient lookup is due to a positive feedback effect: incorrect fingers lead to longer lookup, which at some point cannot be fixed since lookup is too slow to allow fixing the fingers (the network has changed in the meanwhile)
- In our own situation, things are not so simple
  - Input network parameters: size n (number of nodes), successor list redundancy f (small integer), failure suspicion rate r ($0 \le r \le 1$), churn c ($0 \le c \le 1$, rate of node turnover)
  - n and f are imposed by system structure, r and c are imposed by environment
  - Output network parameters: perfection p ($0 \le p \le 1$), entropy s ($0 \le s \le n \cdot \ln(n)$), lookup efficiency e ($e \ge 1$, as compared to best fingers), lookup inconsistency rate i ($0 \le i \le 1$)

Simulation study

- We are currently performing simulations to study the behavior of practical structured overlay networks
  - Chord: simplest system, uses locking and periodic stabilization
  - P2PS: relaxed ring with merge algorithm, uses no locking
- This is work in progress in the SELFMAN project

Design methodology

- Design software systems as a set of interacting feedback loops
  - Each feedback loop controls part of the system
  - The feedback loops interact to manage the overall system
  - Phase transitions will occur naturally as a result of external parameters
- Design software systems so that phase transitions are reversible
  - They will "self heal" when the external stress causing the transition is removed
  - This may require the design of specialized algorithms (e.g., structured overlay network with merge algorithm)
- What design methodology should we use?
  - We need to design for a desired system behavior
  - Analytic study is prohibitive and simulation is only indicative
- Research agenda: create a methodology usable in practical software development
  - First approach (intuitive): study existing systems and derive design rules
  - Second approach (rigorous): prove correctness of design rules by using translations to process calculi

Some conclusions

- To increase robustness and adaptiveness, software can be designed as interacting feedback loops
  - By analogy from the physical and biological sciences
- Phase transitions are a natural consequence of feedback loop architectures
  - For robustness, we need to design reversible phase transitions
- We need a methodology for designing these systems
  - How to design a feedback loop structure to achieve desired robustness
  - How to achieve the desired phases and phase transitions
  - There is a research agenda here