

VERIFICATION OF THE CHORD PROTOCOL,

WITH A

SURPRISING INVARIANT

Pamela Zave

AT&T Laboratories—Research

Bedminster, New Jersey, USA

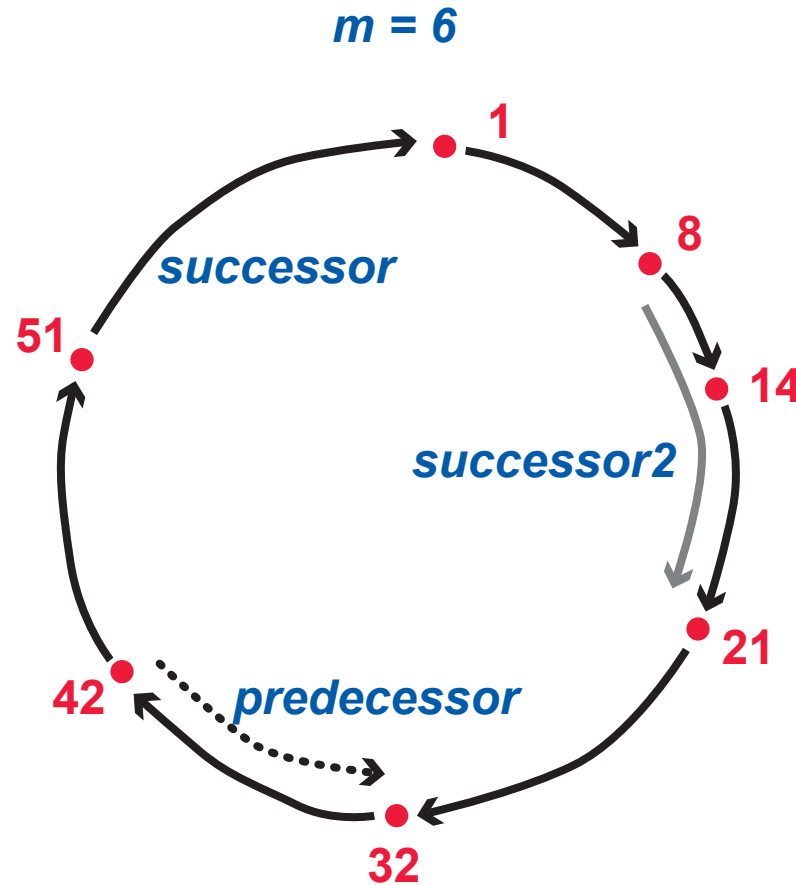
THE CHORD PROTOCOL MAINTAINS A PEER-TO-PEER NETWORK

identifier of a node (assumed unique) is an m -bit hash of its IP address

nodes are arranged in a ring, each node having a successor pointer to the next node (in integer order with wraparound at 0)

redundant pointers support fault-tolerance (extra successors, predecessors)

the protocol preserves the ring structure as nodes join, leave silently, or fail



THE PROTOCOL IS INTERESTING

- no central administration (almost)
- communication in the network is fast
- protocol operations are simple and fast:

no timing constraints (almost)

no multi-node atomic operations

WHY IS CHORD IMPORTANT?

*the 2001 SIGCOMM paper introducing Chord
is one of the most-referenced
papers in computer science, . . .*

. . . and won SIGCOMM's 2011 Test of Time Award

APPLICATIONS

- allows millions of *ad hoc* peers to cooperate
- used as a building block in fault-tolerant applications
- often used to build distributed key-value stores (where the key space is the same as the Chord identifier space)
- the best-known application is BitTorrent

RESEARCH ON PROPERTIES AND EXTENSIONS

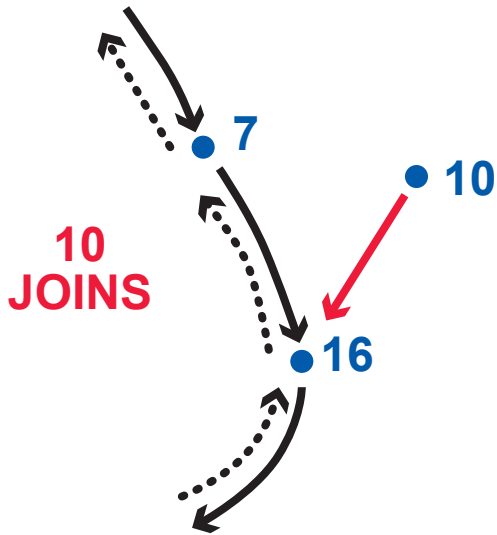
- protection against malicious peers
- key consistency (all nodes agree on which node owns which key), replicated data consistency

“Three features that distinguish Chord from many other peer-to-peer lookup protocols are . . .

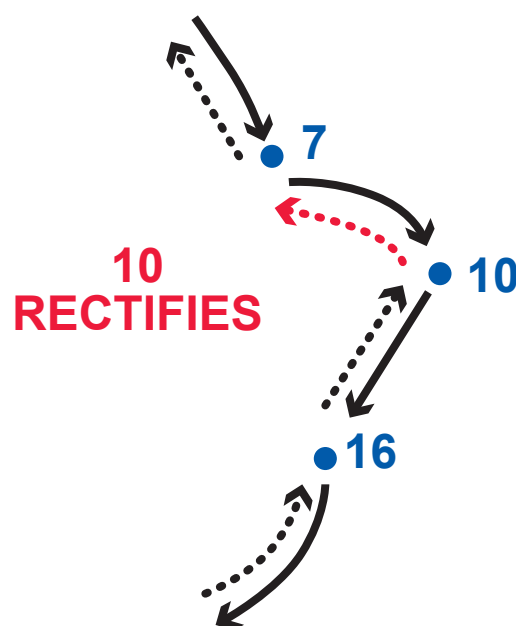
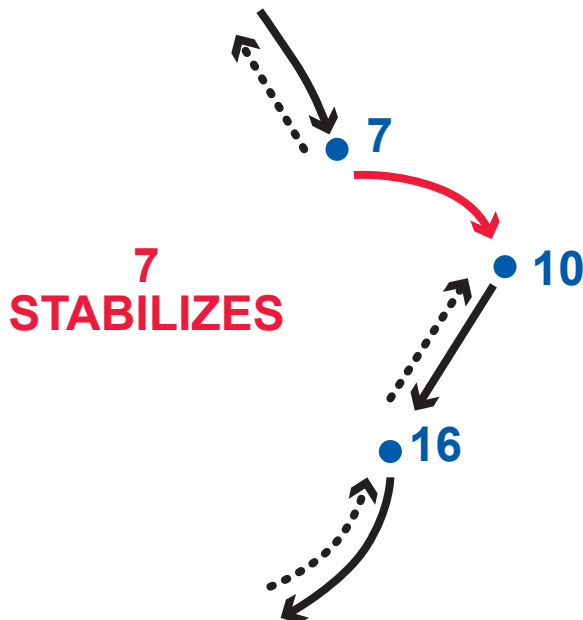
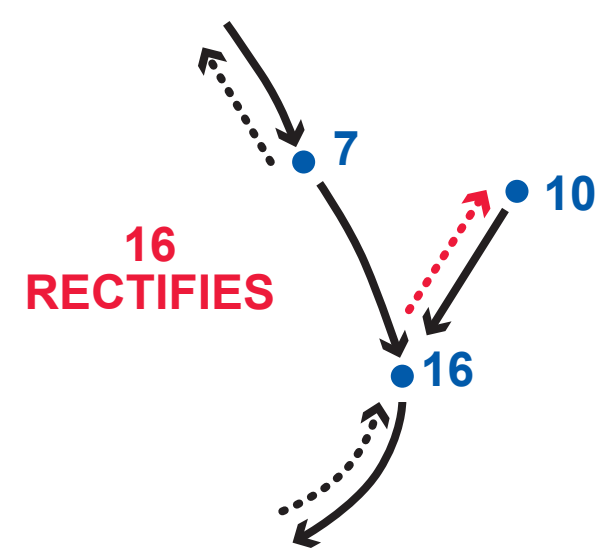
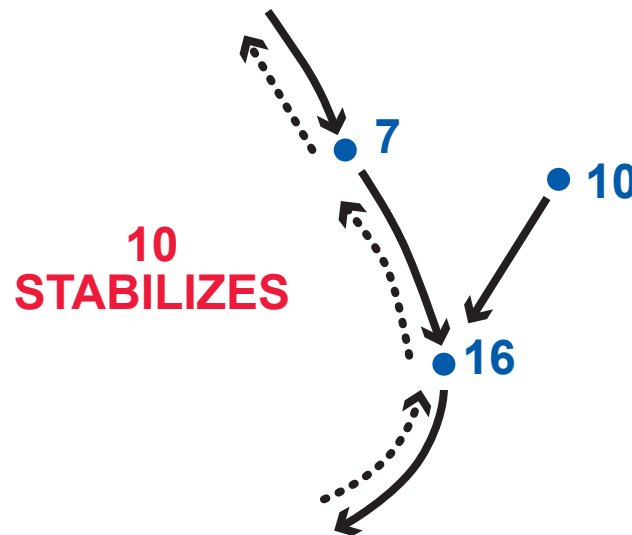
. . . its simplicity,
. . . **provable correctness**,
. . . and provable performance.”

OPERATIONS OF THE PROTOCOL

an operation changes the state of one member



Join and Stabilize are scheduled autonomously, Rectify is caused by another member's Stabilize



in addition, a member can Fail (or leave) silently

there is perfect failure detection

Stabilizing member detects a dead successor and promotes its next successor

THE CLAIMS

Correctness Property:

In any execution state, IF there are no subsequent Join or Fail events, . . .

. . . THEN eventually . . .

. . . all pointers in the network will be globally correct, and remain so.

THE REALITY

- even with simple bugs fixed and optimistic assumptions about atomicity, the original protocol is not correct
- of the seven properties claimed invariant of the original version, not one is actually an invariant

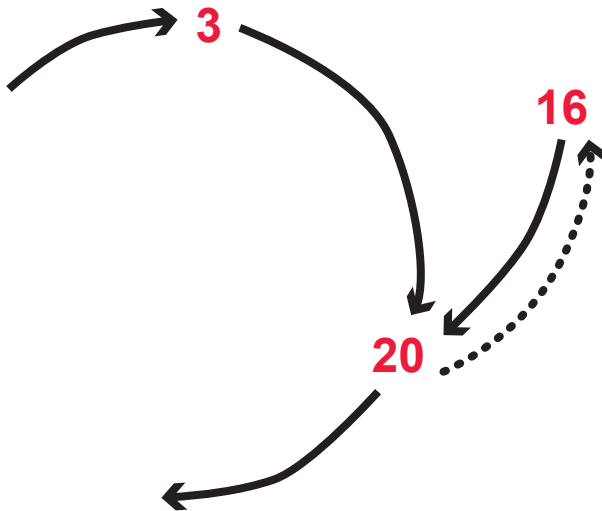
I found these problems by analyzing a small Alloy model

Chris Newcombe and others at AWS credit this work with overcoming their bias against formal methods, which they now use to find bugs.

[CACM, April 2015]

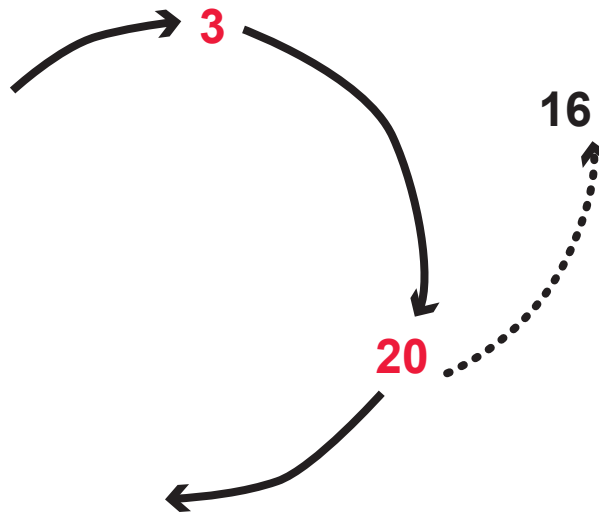
not surprisingly, all due to sloppy informal specification and proof

A TYPICAL BUG IN ORIGINAL CHORD



3 has no *successor2* yet (it is not required to have all successors filled in)

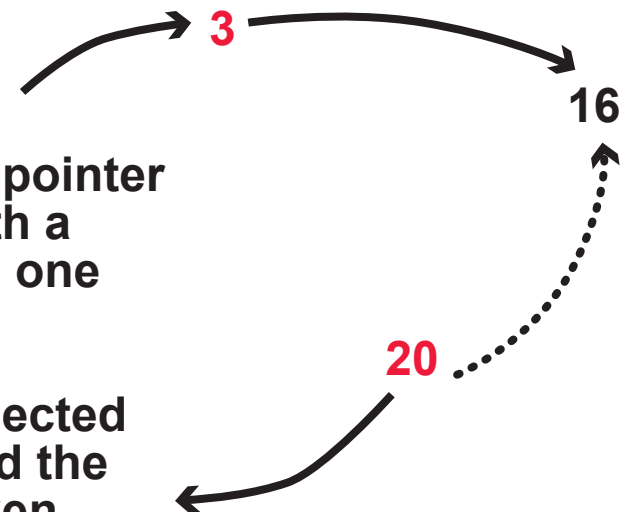
16 FAILS



3 STABILIZES

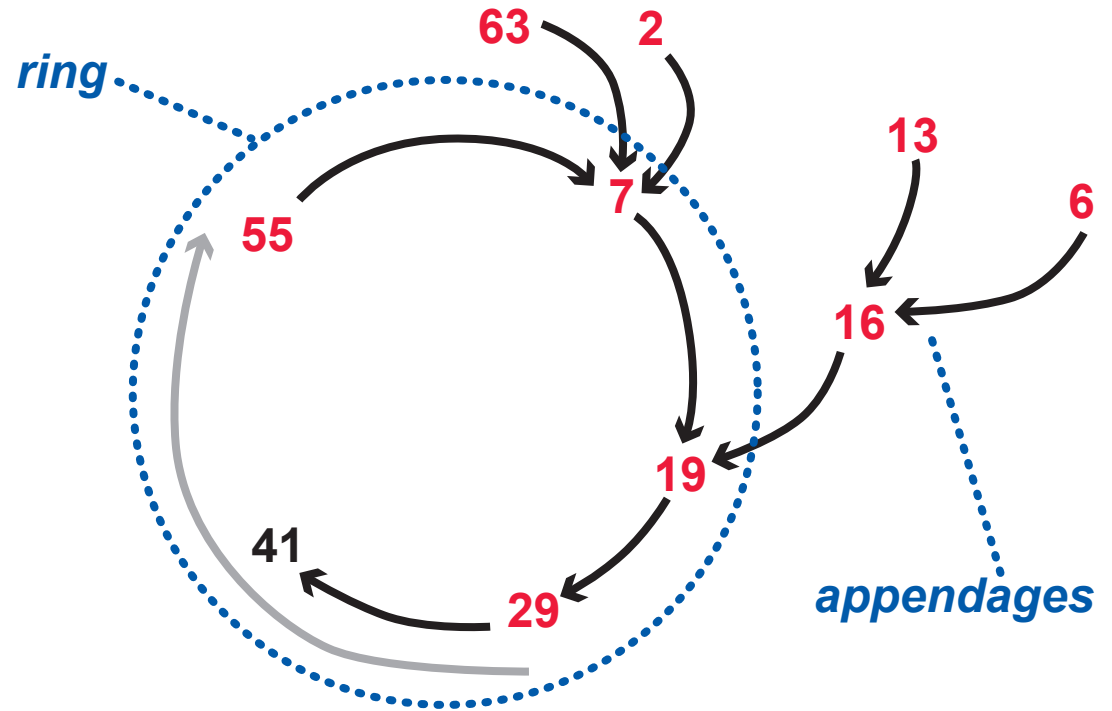
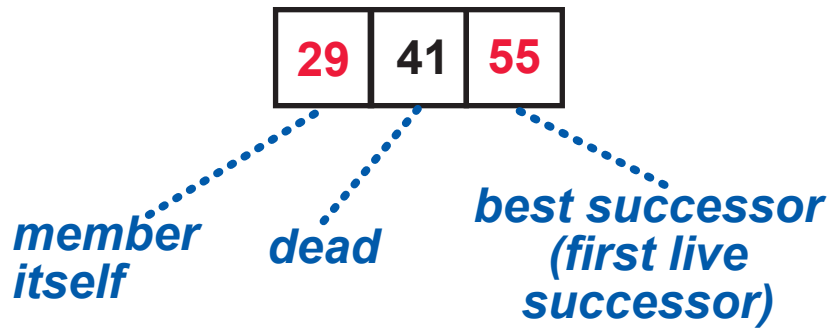
3 has replaced a pointer to a live node with a pointer to a dead one

now 3 is disconnected from the ring, and the ring may be broken



BASIC CORRECTNESS STRATEGY 2

extended successor list (ESL)
of 29 (with $L = 2$):



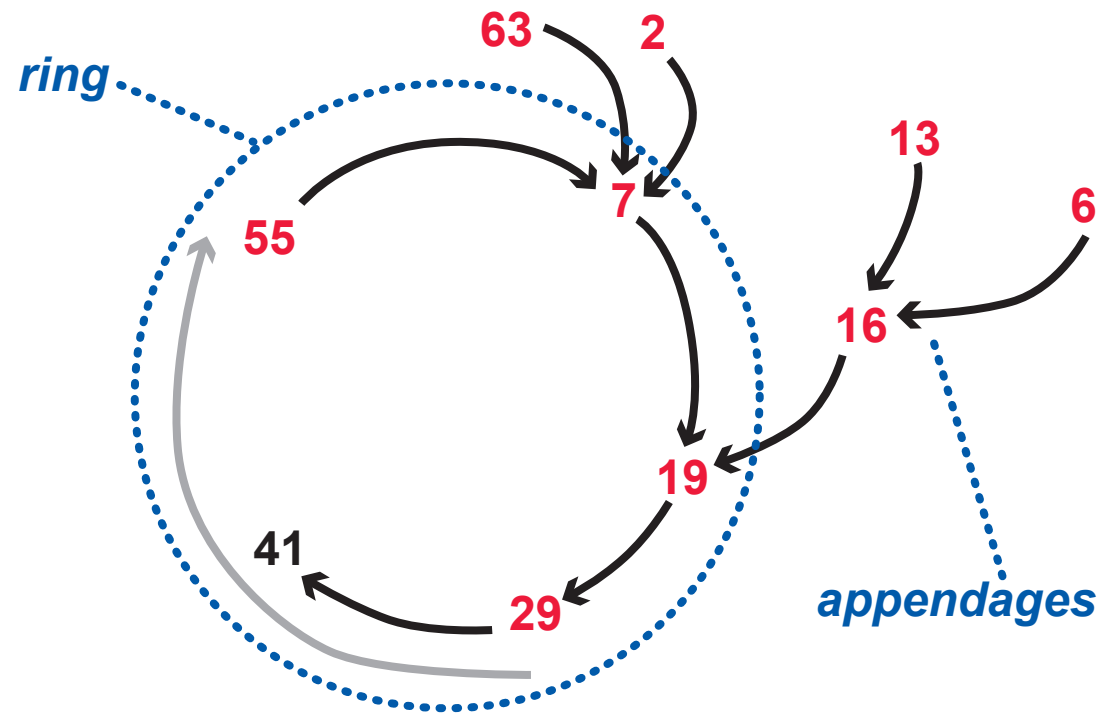
Definition of *FullSuccessorLists*:
The extended successor list of each member has $L+1$ distinct entries.

New operating assumption:

If a Chord network has the property *FullSuccessorLists*, then no failure leaves a member without a live successor.

**if not satisfied for the real failure rate,
... increase rate of stabilization,
... or increase redundancy**

BASIC CORRECTNESS STRATEGY 3



TO MAKE ORIGINAL CHORD CORRECT:

- alter the initialization to satisfy *FullSuccessorLists* with all members live
requires $L+1$ members
- alter the operations to populate successor lists more eagerly, so that they always have L entries

now it is roughly correct (in hindsight) but how do we prove it without an invariant?

WHY IS FINDING AN INVARIANT SO DIFFICULT?

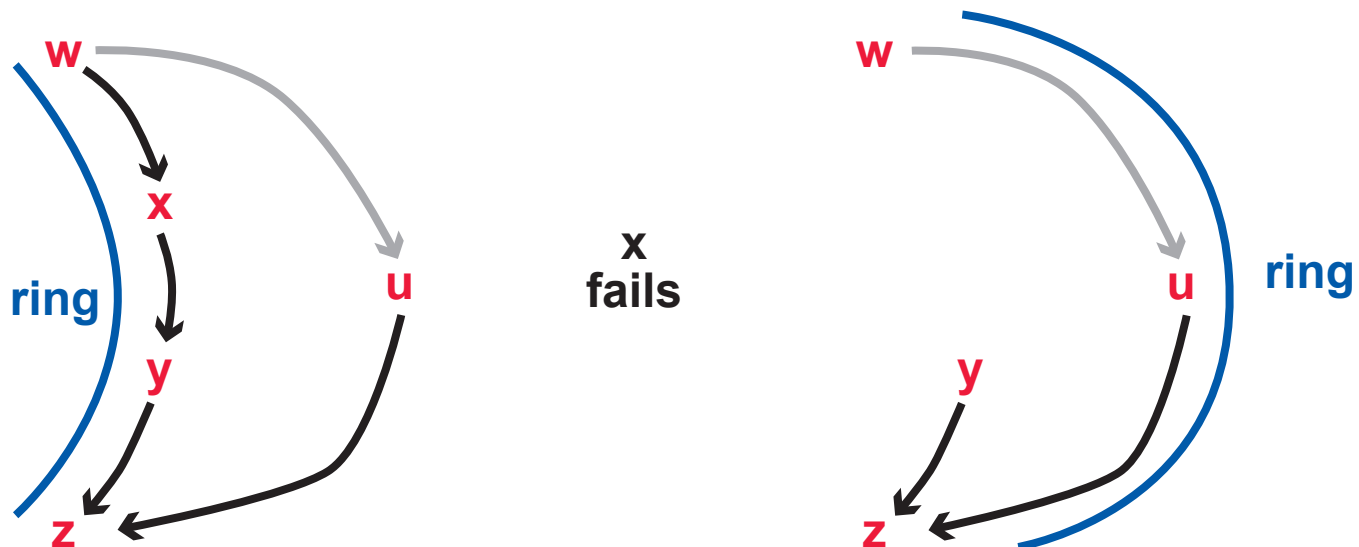
THE KNOWN, NECESSARY PROPERTIES ARE STATED IN TERMS OF THE RING . . .

- there is a ring of best successors
- there is no more than one ring
- on the unique ring, the members are in identifier order
- from each appendage member, the ring is reachable through best successors

about the ring of best successors

about the appendages

. . . BUT “RING VERSUS APPENDAGE” IS CONTEXT-DEPENDENT AND FLUID:



AN INTERMEDIATE RESULT

ANOTHER OPERATING ASSUMPTION:

A chord network has a *stable base* of $L+1$ nodes that are always members.

expensive to implement these high-availability nodes!

a stable base would have 3-6 members, while a Chord network can have millions of members—what is the base doing?

THE INDUCTIVE INVARIANT:

AtLeastOneRing

and *AtMostOneRing*

and *OrderedRing*

and *ConnectedAppendages*

and *BaseNotSkipped*

I believe it is just preventing anomalies in small networks, but how can we know for sure?

no successor list skips over a member of the stable base

THE PROOF OF CORRECTNESS:

by exhaustive enumeration, in Alloy,
for all model instances up to $N = 9$, $L = 3$

THE FINAL RESULT

ANOTHER OPERATING ASSUMPTION:

None

THE INDUCTIVE INVARIANT:

OneLiveSuccessor
and *SufficientPrincipals*

this is just a formalization
of the original operating
assumption

Definition of a *principal member*:
A member that is not skipped by any
member's successor list.

Definition of *SufficientPrincipals*:
There are at least $L+1$ principal nodes.

THE PROOF OF CORRECTNESS:

informal and intuitive, but . . .

. . . a real proof (no size limits)

. . . backed up by an Alloy model checked up to $N = 9$, $L = 3$
(as a protection against human error)

the “stable base” has become
something we can prove, rather than
an assumption!

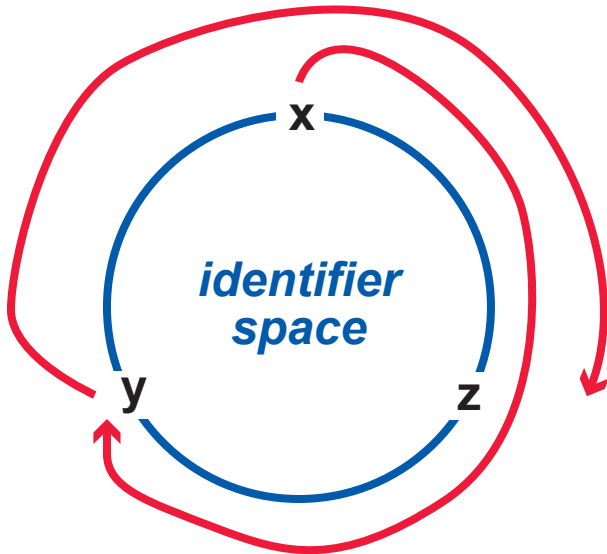
ORDERED (AND FULL) SUCCESSOR LISTS . . .

. . . ARE IMPLIED BY THE INVARIANT

Definition of *OrderedSuccessorLists*:
For all sublists $[x, y, z]$ of an ESL
(whether the sublist is contiguous
or not) . . .

between $[x, y, z]$.

hypothesize a
disordered extended
successor list
[. . . x, . . . y, . . . z, . . .]



Proof of *OrderedSuccessorLists*

the only identifier in the
entire space that is not
skipped by $[x, \dots y, \dots z]$
is y

picture

principal nodes cannot
be skipped by a
successor list

definition

there must be at least
 $L + 1$ principal nodes,
where L is greater than
or equal to 1

*Sufficient
Principals*

CONTRADICTION!

THE PRINCIPAL NODES MAKE THE SHAPE OF THE RING

every member has a best successor (first live successor)

there are sufficient principal nodes

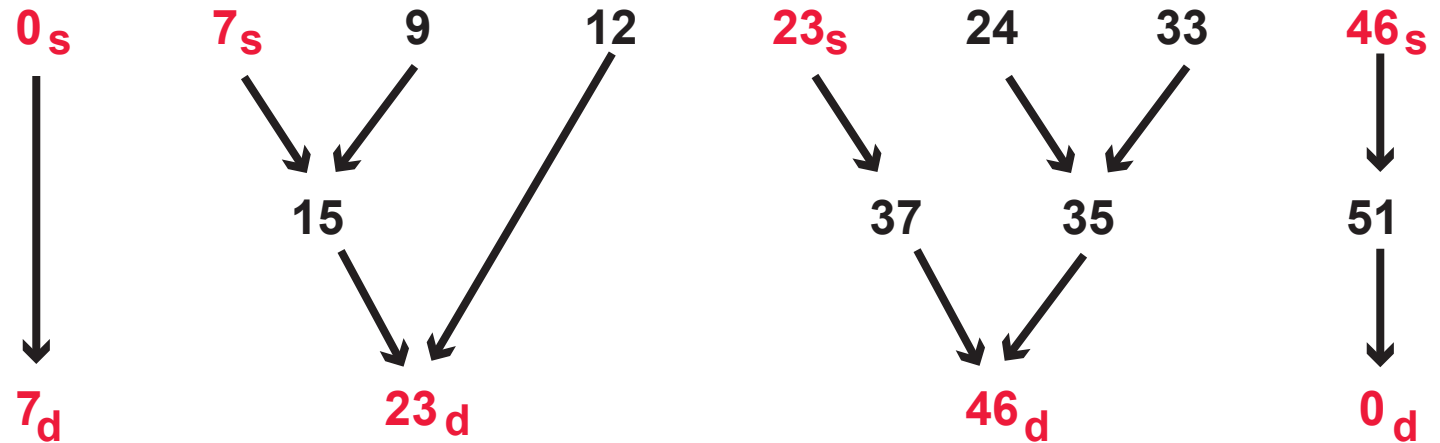
here is a graph of best successors:

these paths . . .

. . . do not skip principal nodes

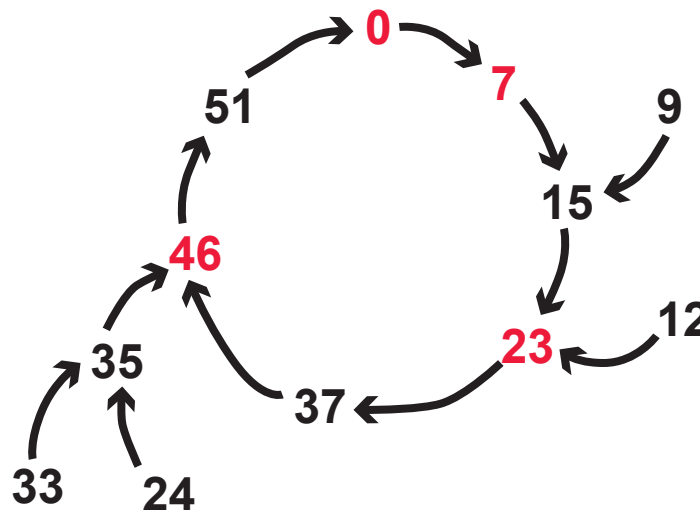
. . . are acyclic

. . . are ordered by identifiers



each tree has exactly one p_s , which is unique to it

so the re-arranged graph must look like this



automatically satisfying *OneOrderedRing* and *Connected-Appendages*

CONCURRENCY AND COMMUNICATION

AN OPERATION IS A SEQUENCE OF ATOMIC STEPS

EACH ATOMIC STEP IS AN INTERNAL STATE CHANGE OR THIS:

atomic step at X

node X

node Y

query message

formal model has a shared-state abstraction

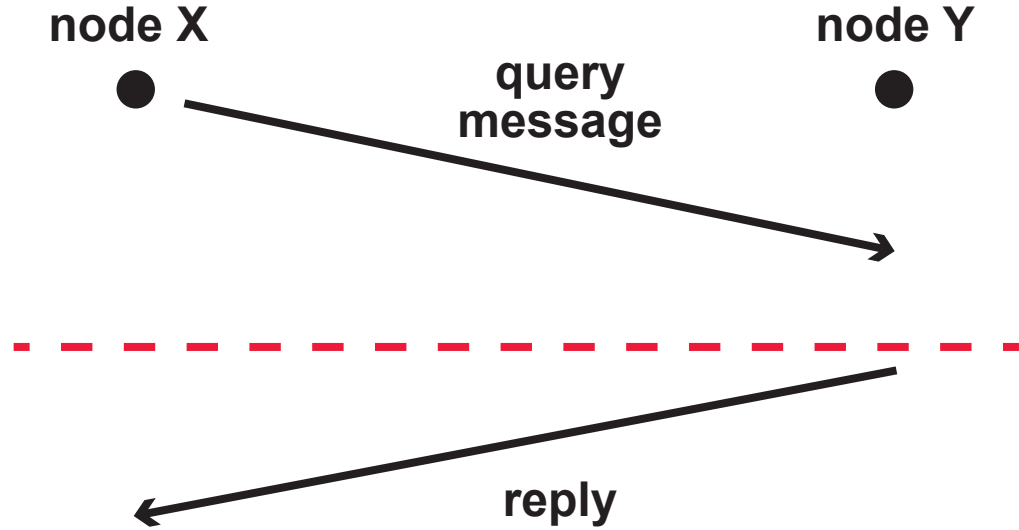
step can be assumed to occur at this instant

reply message

X changes state

while waiting for a reply (or timeout), X cannot answer queries about its state

because of the structure of operations, queries cannot form circular waits



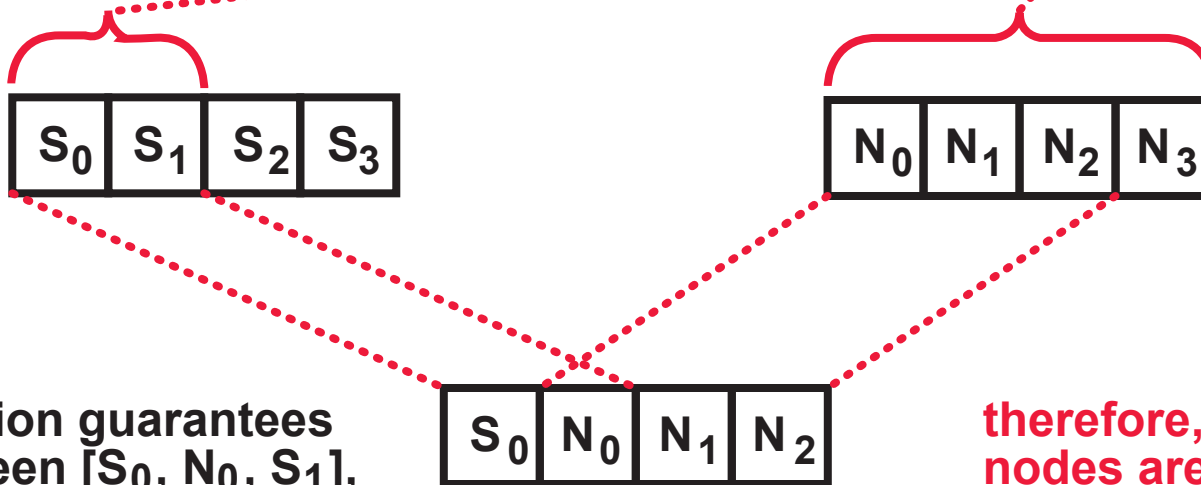
HOW STABILIZE PRESERVES THE INVARIANT

JOIN AND
RECTIFY
ARE SIMILAR

extended successor list of
stabilizing node, before Stabilize

extended successor list
of its new successor

because invariant holds, no
current principal nodes are skipped
here or here



precondition guarantees
that between $[S_0, N_0, S_1]$,
so no current principal
nodes are skipped from
 S_0 to N_0

therefore, no former principal
nodes are skipped by this new
successor list, and the number
of principal nodes has not
decreased

some Chord operations
need multiple atomic steps



in the new, provably correct, specification,
every intermediate operation state is also
constructed in this safe way

HOW FAIL PRESERVES THE INVARIANT

PRESERVATION OF *OneLiveSuccessor*

The operating assumption is that no failure leaves a member with no live successor, . . .

. . . so the invariant is assumed to be preserved.

PRESERVATION OF *SufficientPrincipals*

Lemma: The only operation that can cause a node to change from principal to non-principal is its own failure.

Why can't failure of a principal node leave the network with fewer than $L+1$ principals?

The life history of a long-lived member:

- 1 Join
- 2 become principal because all neighbors know you
- 3 enjoy life as a principal node
- 4 Fail

Therefore the number of principal nodes is proportional to the number of nodes.

Once the network has grown (especially to millions of members!) it is overwhelmingly improbable that it will have fewer than 3-6 principal nodes.

PROVING PROGRESS

IF THERE ARE NO MORE
JOIN OR FAIL EVENTS . . .

. . . WHILE MEMBERS
CONTINUE TO STABILIZE . . .

1 dead successors are removed, so that every member's first successor is live

2 every member's first successor and predecessor become globally correct

3 tails of all successor lists become correct

as with construction of intermediate successor lists, operations must be specified precisely to ensure correctness

here preconditions must ensure that no operation reverses the progress of a past or current phase

CONCLUSIONS

THE PRODUCT

- initialization is more difficult than original Chord, but a simple protocol will get networks off to a safe start
- otherwise correct Chord is just as efficient as original Chord

it is an impressive pattern for fault-tolerance

- these peer-to-peer protocols have a (justified) reputation for unreliability
- a correct specification could pave the way for a new generation of reliable, more useful implementations

it also provides a firm foundation for work on better failure detection and security

THE PROCESS

- Chord is a very interesting protocol—note that the invariant looks nothing like the properties we care about!
- results would have been impossible to find without model-checking to explore bizarre cases and get ideas from them

that is where the idea of a stable base came from

- the best result was impossible to find without the insights that came from the proof process

`www.research.att.com/~pamela`
> How to Make Chord Correct

PATTERNS IN NETWORK ARCHITECTURE:

PRINCIPLES FOR LAYERING

PERFORMANCE SERVICES

QoS

reliability

mobility

Simplifying Assumption:

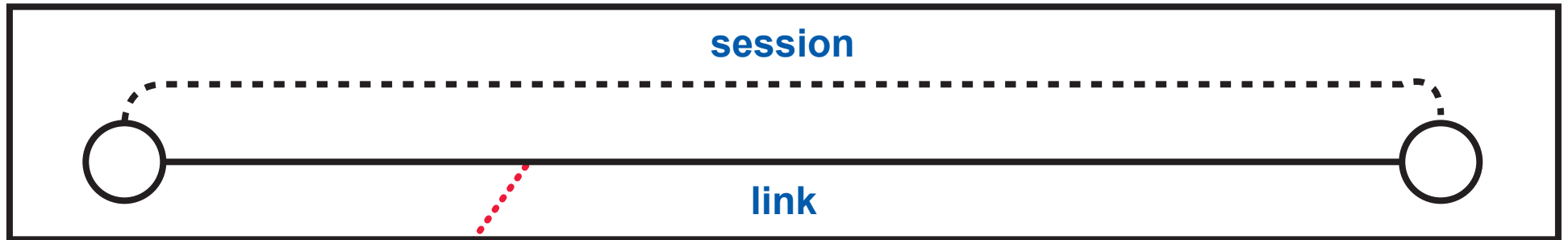
There is no multihoming.

SECURITY SERVICES

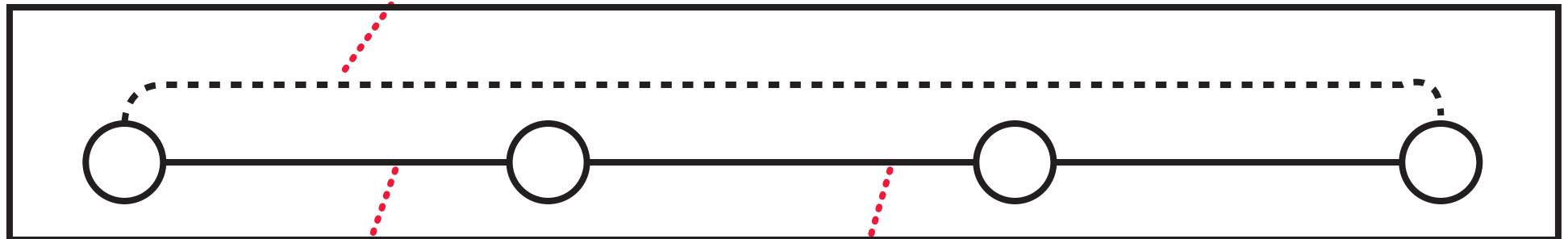
data integrity

packet filtering

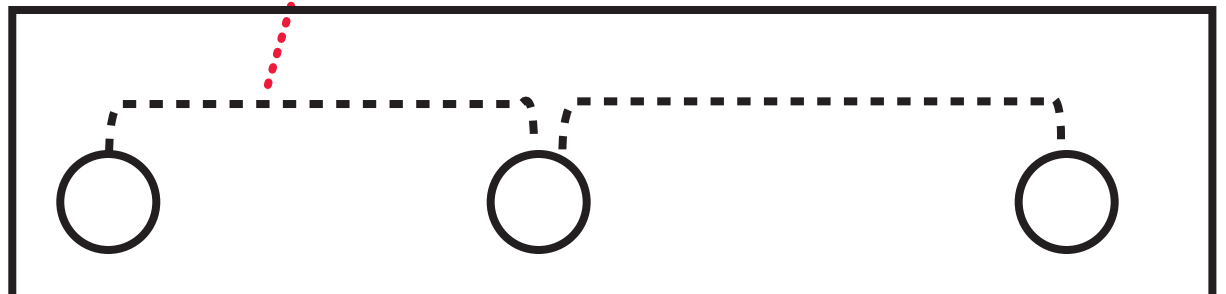
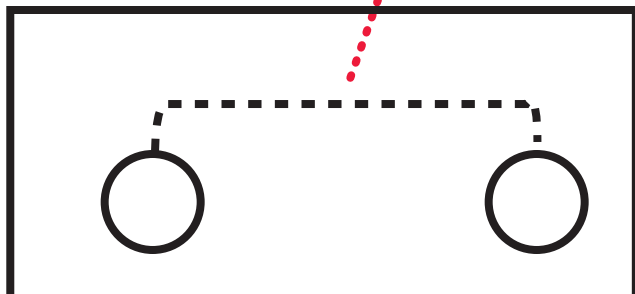
BASIC LAYERING



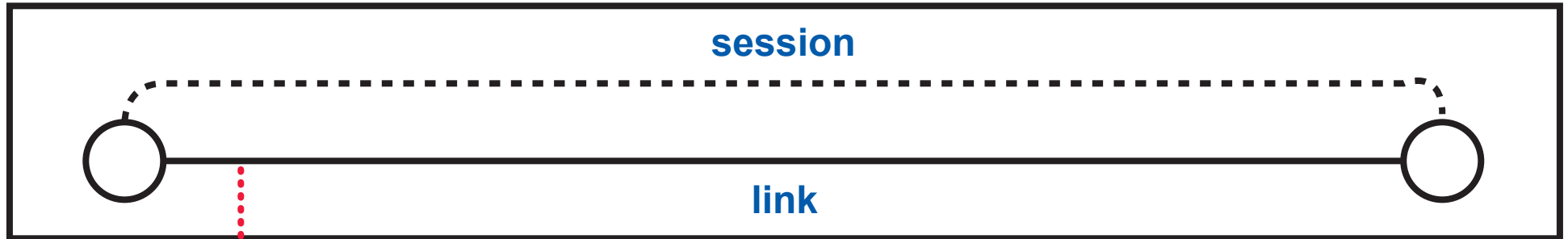
an overlay link is implemented by an underlay session



links of a network can be implemented by sessions in one or several networks



BEST-EFFORT POINT-TO-POINT SERVICE (QUANTIFIED)



PROPERTIES OF THE LINK

- packets are sent at the rate of B
- with probability P , a packet arrives within time L
- in addition to loss or delay, packets can be re-ordered or duplicated in transit

THE UNDERLAY SESSION IMPLEMENTS THIS SERVICE

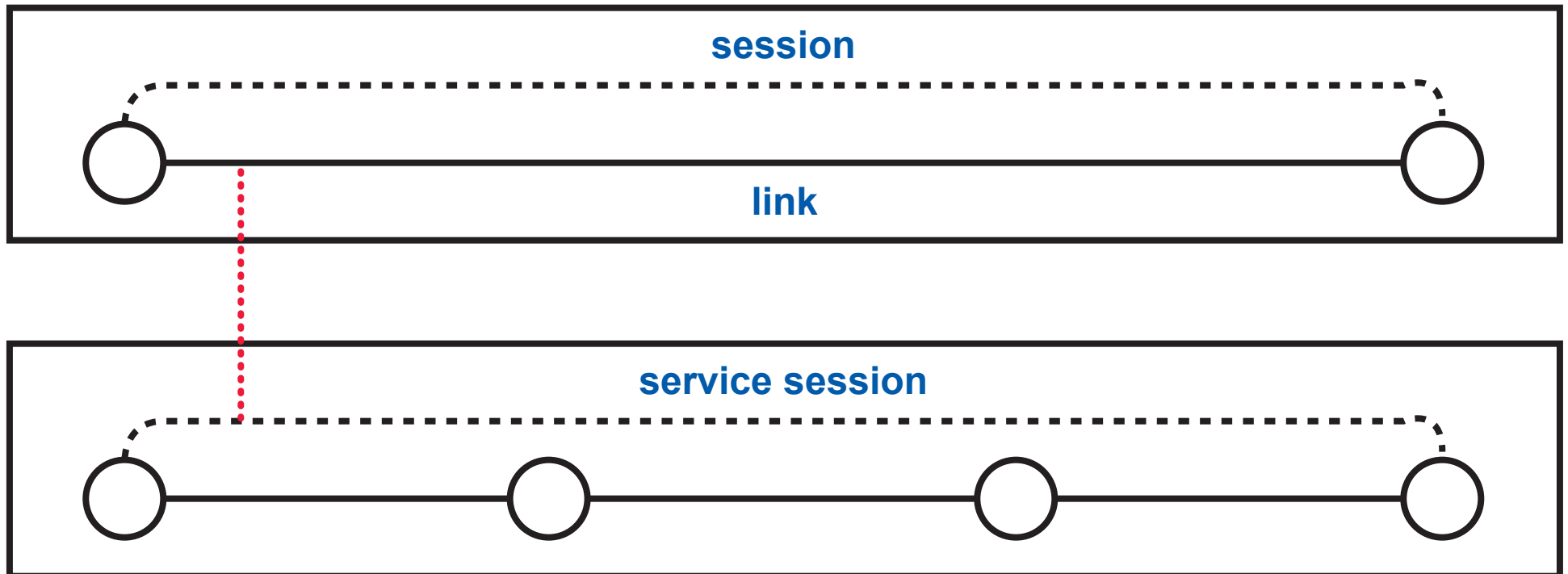


PRINCIPLES FOR LAYERING

As we have seen in this class, there are **MANY** services a network could implement.

How do these services compose in a network architecture?

Where in a network architecture should a service be implemented?



COMPOSITION OF “QUALITY OF SERVICE” SERVICE (QUANTIFIED SERVICE WITH GUARANTEES)

for each link in the path of the session, let S_j be the fraction of the link's bandwidth allocated to the session

minimum bandwidth = $\min_j (S_j (B_j))$

minimum success probability = $\prod_j (P_j)$

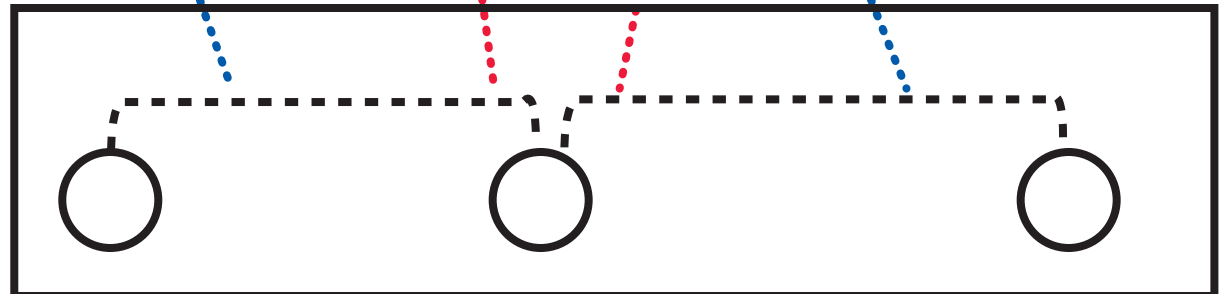
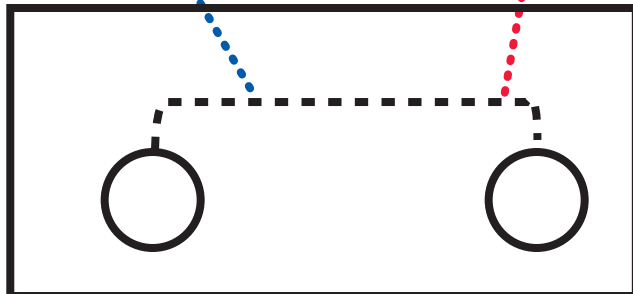
maximum latency = $\sum_j (L_j) + \sum_j (D_j)$



min. bandwidth B_1
min. success prob. P_1
maximum latency L_1

min. bandwidth B_2
min. success prob. P_2
maximum latency L_2

min. bandwidth B_3
min. success prob. P_3
maximum latency L_3



COMPOSITION OF RELIABILITY SERVICE (FOR EXAMPLE, TCP)

this session is reliable if . . .

. . . all the links in its path are reliable, and

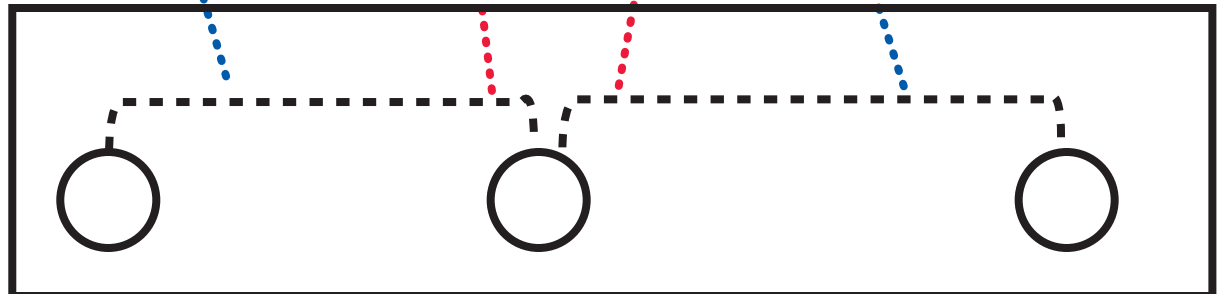
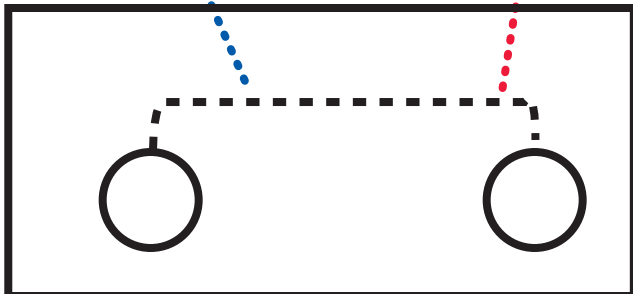
. . . all the network nodes in its path are reliable



packets are delivered reliably and in the order they were sent

packets are delivered reliably and in the order they were sent

packets are delivered reliably and in the order they were sent



COMPOSITION OF DATA-INTEGRITY SERVICE (FOR EXAMPLE, IPsec)

this session has data integrity if . . .

. . . all the links in the path have data integrity, and

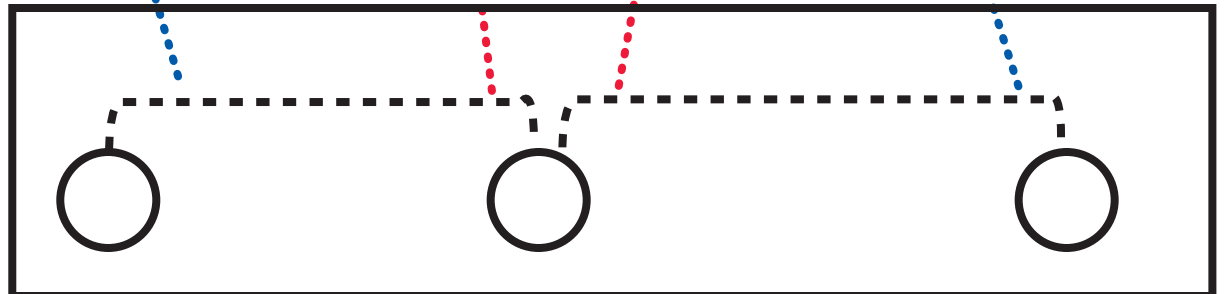
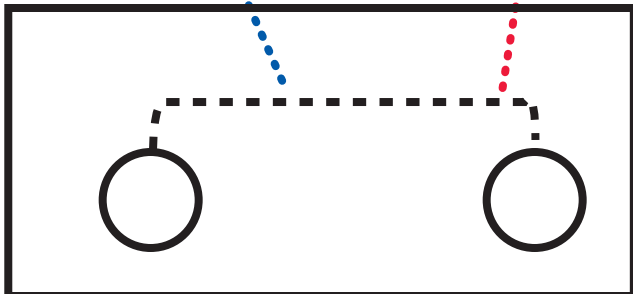
. . . all the network nodes in the path can be trusted to preserve integrity



no node except the session endpoints can read or change the data.

no node except the session endpoints can read or change the data.

no node except the session endpoints can read or change the data.

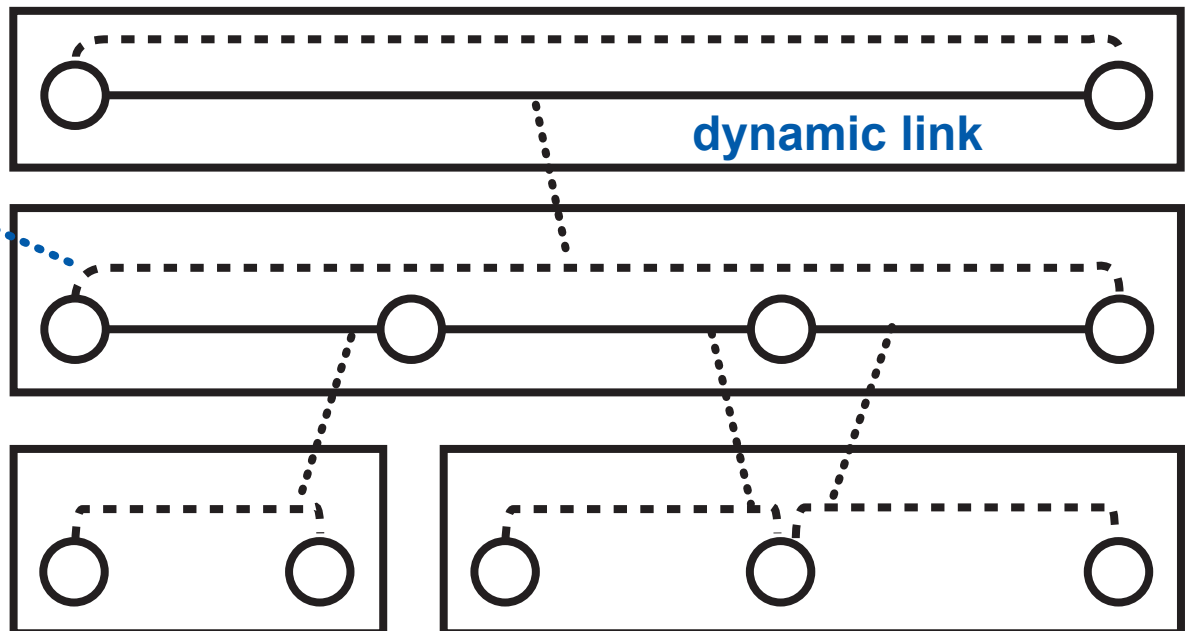


SERVICE	WHERE NEEDED?	WHERE IMPLEMENTABLE?	HOW PROPAGATED?	RESULT?
QoS	top session	where a network can provide sessions with dedicated paths, shorter paths, higher-quality paths, etc.	piecewise	must propagate up to BE2EUS
reliability	top session	any session protocol	piecewise	put in BE2ES or above
data integrity	above any untrusted links or nodes	any session protocol	piecewise	put in bottom session over untrusted span, or above

bottom end-to-end unshared session (BE2EUS)

all properties of this session propagate piecewise to the top

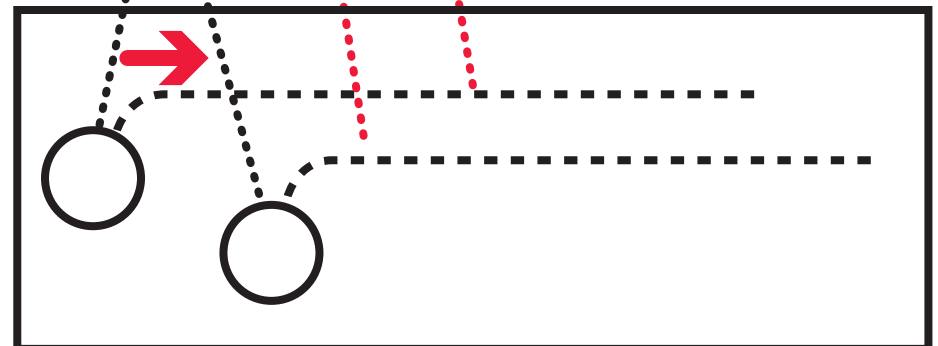
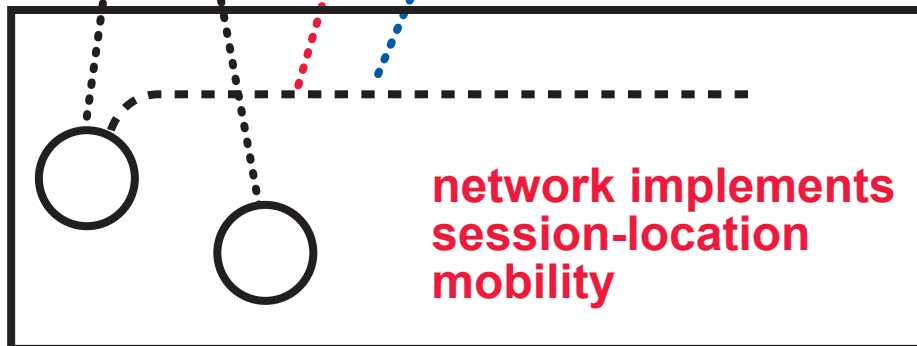
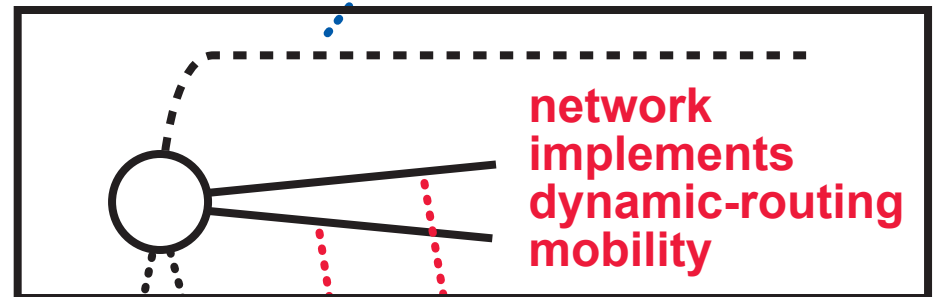
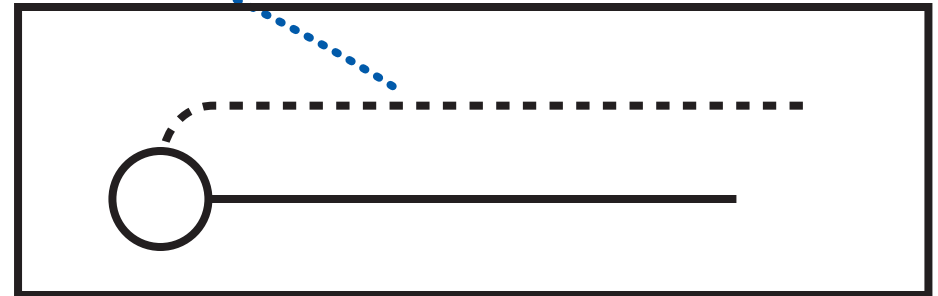
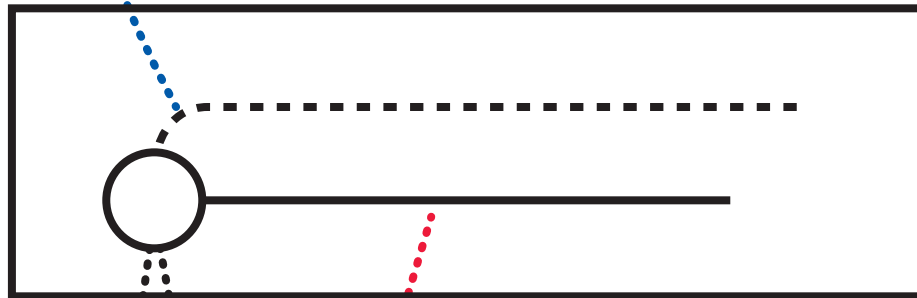
there can also be a bottom end-to-end session (BE2ES)



COMPOSITION OF MOBILITY SERVICE

these sessions are preserved despite mobility if ...

... the links at their endpoints are preserved despite mobility



session preserved despite mobility

session preserved despite mobility

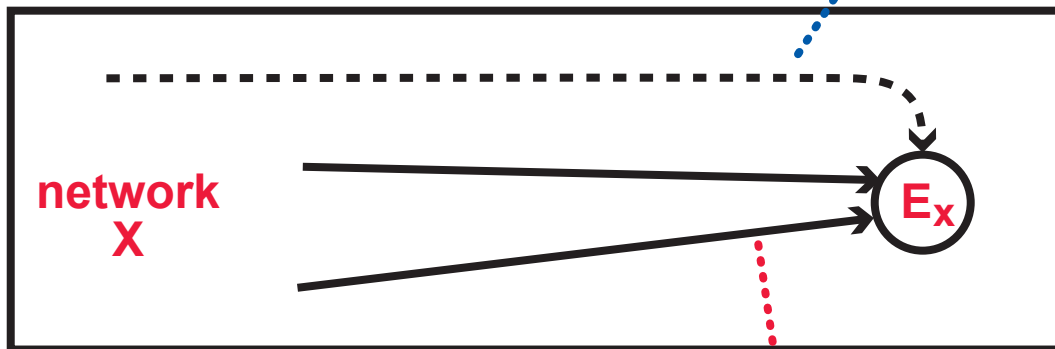
network implements session-location mobility

network implements dynamic-routing mobility

COMPOSITION OF PACKET-FILTERING SERVICE

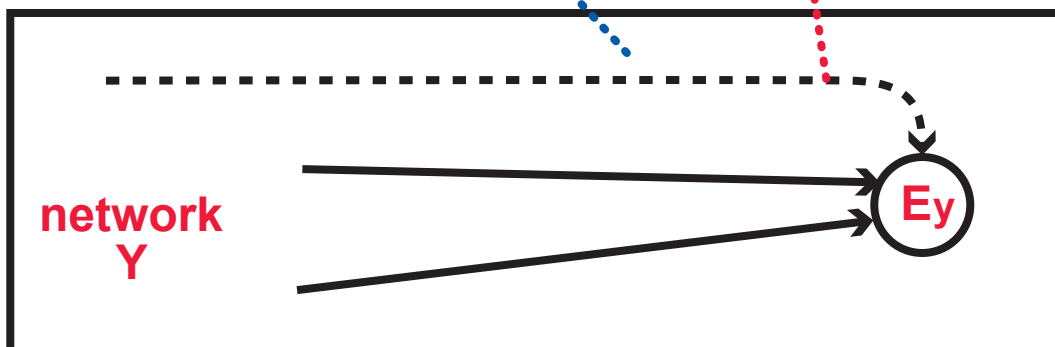
member receives no undesirable session-initiation packets if . . .

. . . it does not receive any undesirable session-initiation packets on its inlinks



it does not matter whether inlinks are static or dynamic

member receives no session-initiation packets that are undesirable for X



implemented by filtering all the inlinks of E_y

how does Y know what is undesirable for X?

SERVICE	WHERE NEEDED?	WHERE IMPLEMENTABLE?	HOW PROPAGATED?	RESULT?
mobility	top session	only where the change of attachment occurs	endpoint attachment	propagation upward is automatic
packet filtering	all network members in a machine	at any level where it is possible to discriminate	endpoint attachment	filter high-volume attacks at a low level, low-volume attacks where discrimination is better