VERIFICATION OF THE CHORD PROTOCOL,

WITH A

SURPRISING INVARIANT

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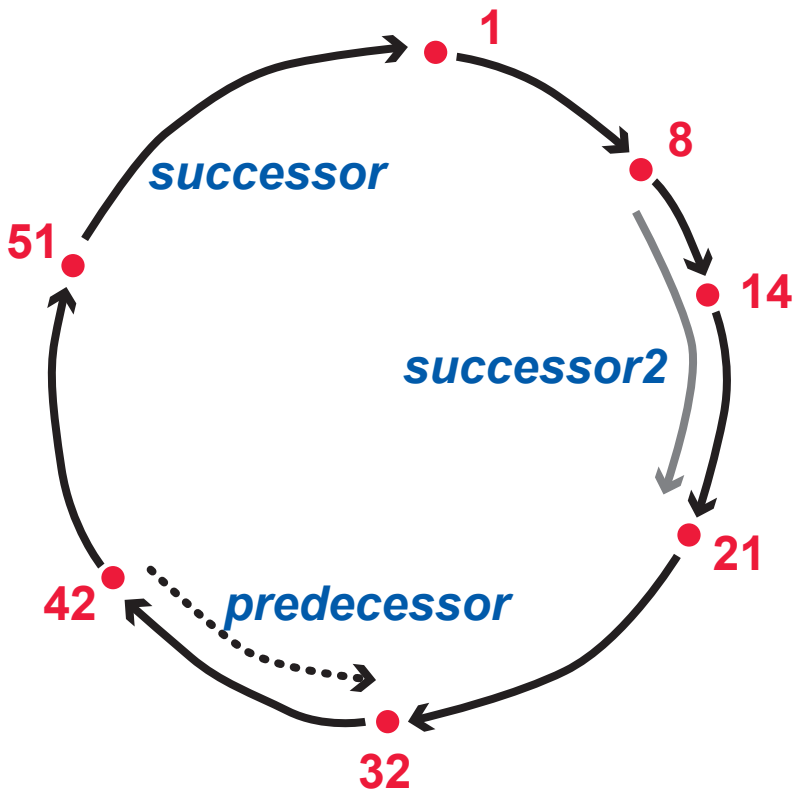
THE CHORD PROTOCOL MAINTAINS A PEER-TO-PEER NETWORK

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

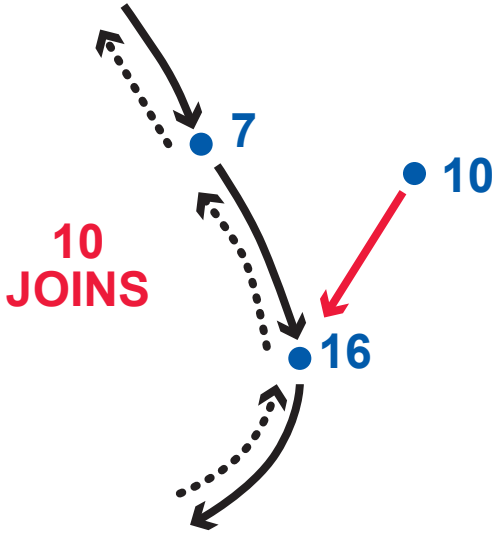
"Three features that distinguish Chord from many other peer-to-peer lookup protocols are . . .

. . . its simplicity,
. . . provable correctness,
. . . and provable performance."

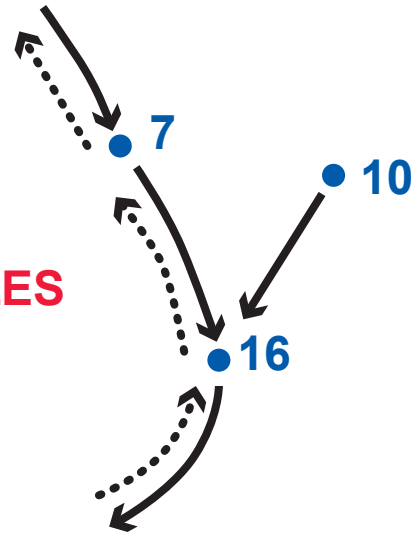
OPERATIONS OF THE PROTOCOL

an operation changes
the state of one member

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



10
JOINS



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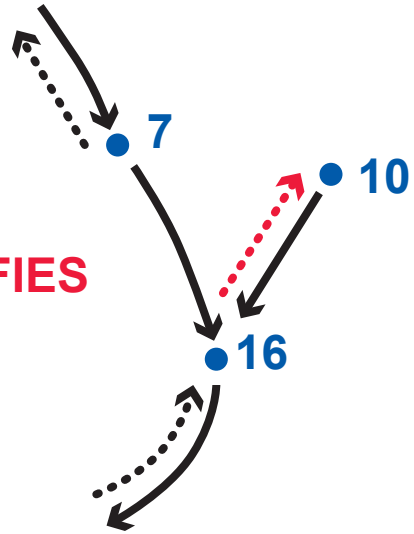
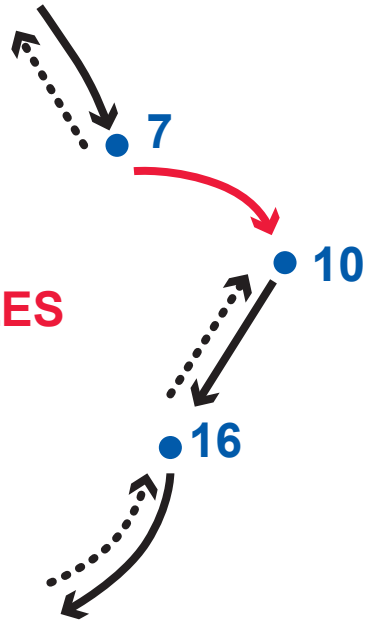
STABILIZES



16
RECTIFIES



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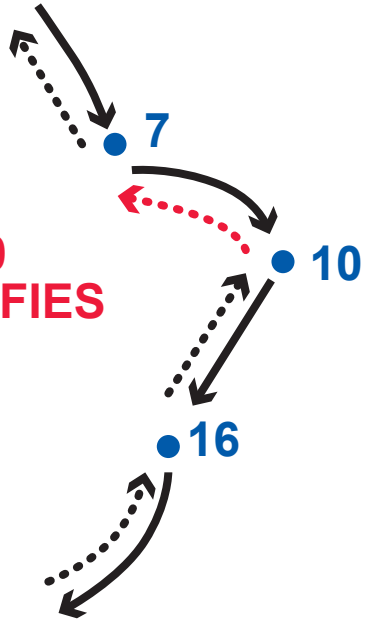
STABILIZES



10
RECTIFIES

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**

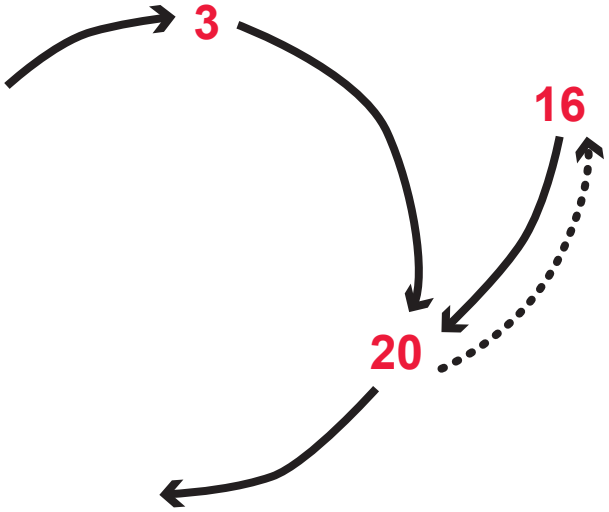
not surprisingly, all due to sloppy informal specification and proof

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.

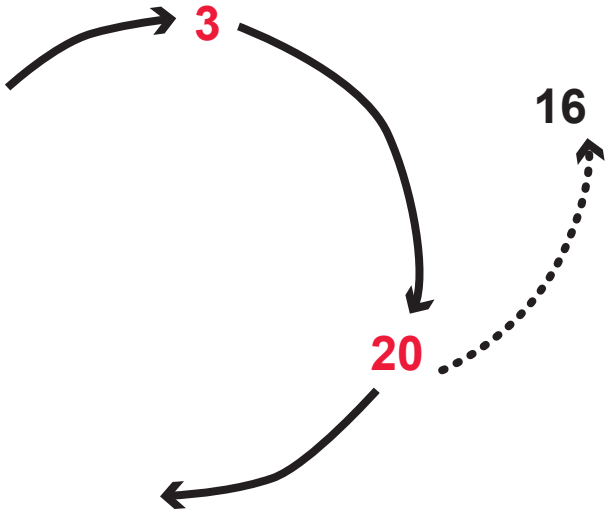
[CACM, April 2015]

A TYPICAL BUG IN ORIGINAL CHORD

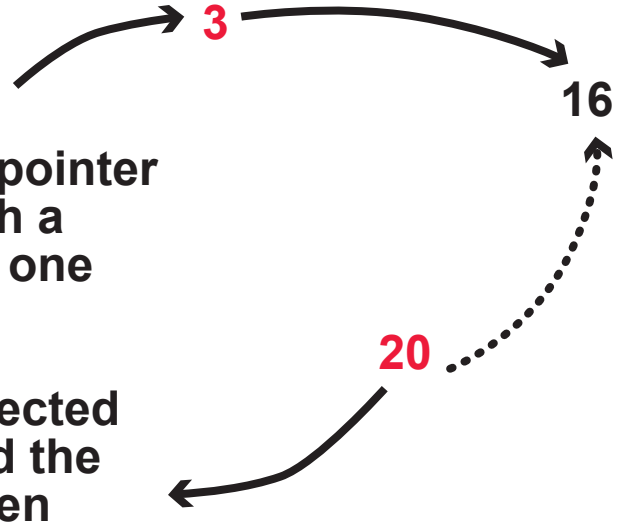


3 has no *successor2* yet (it is not required to have all successors filled in)

16 FAILS



3 STABILIZES

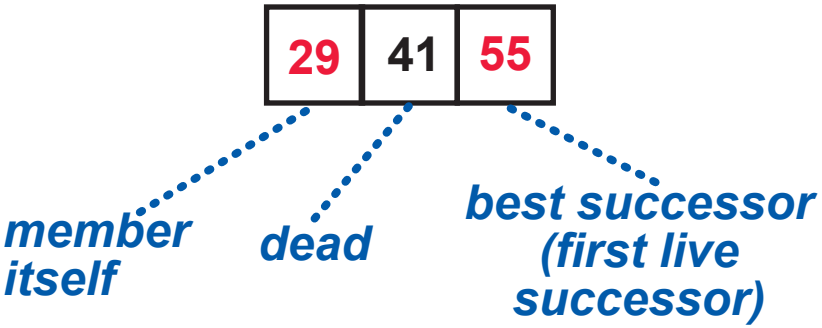


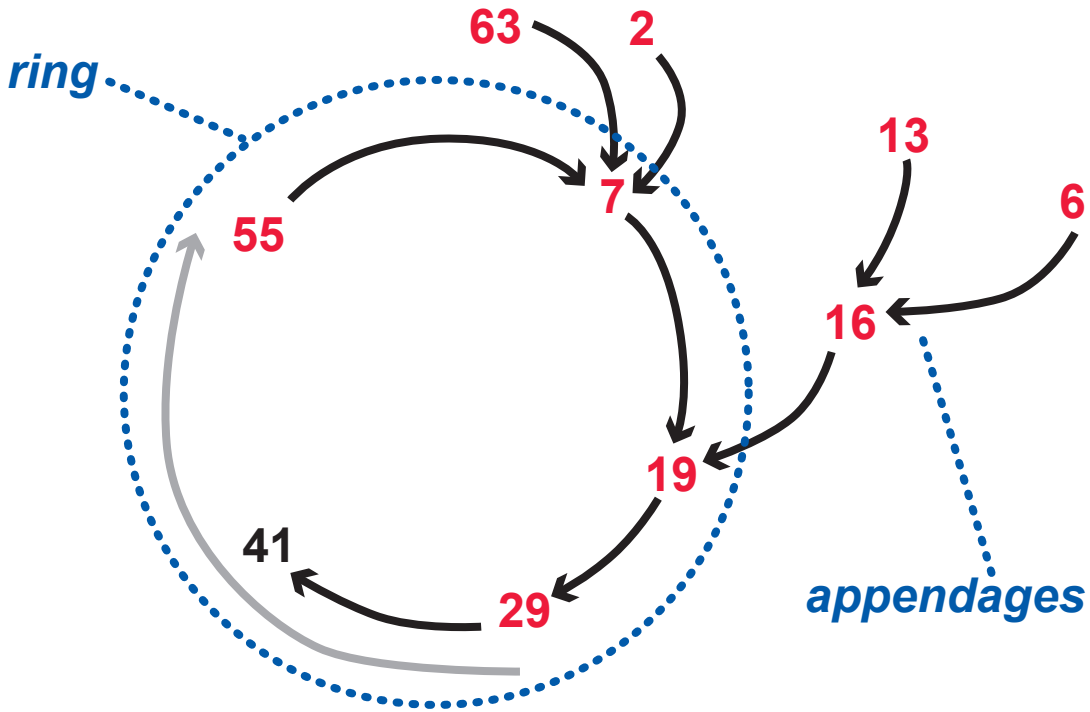
3 has replaced a pointer to a live node with a pointer to a dead one

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

BASIC CORRECTNESS STRATEGY 1

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





Original operating assumption:

No failure leaves a member without a live successor.

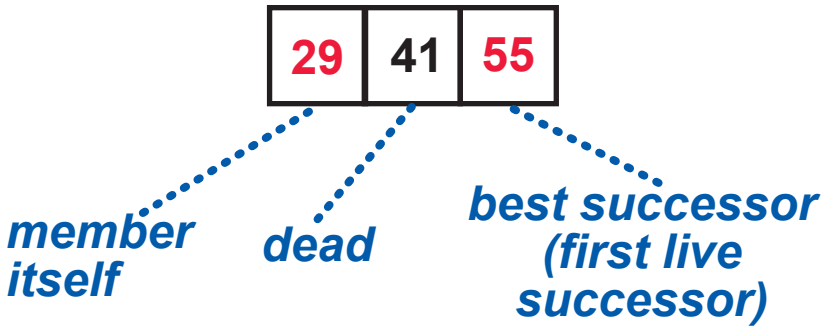
Clearly, with L = 2, Chord is intended to tolerate one failure in a neighborhood, but not two.

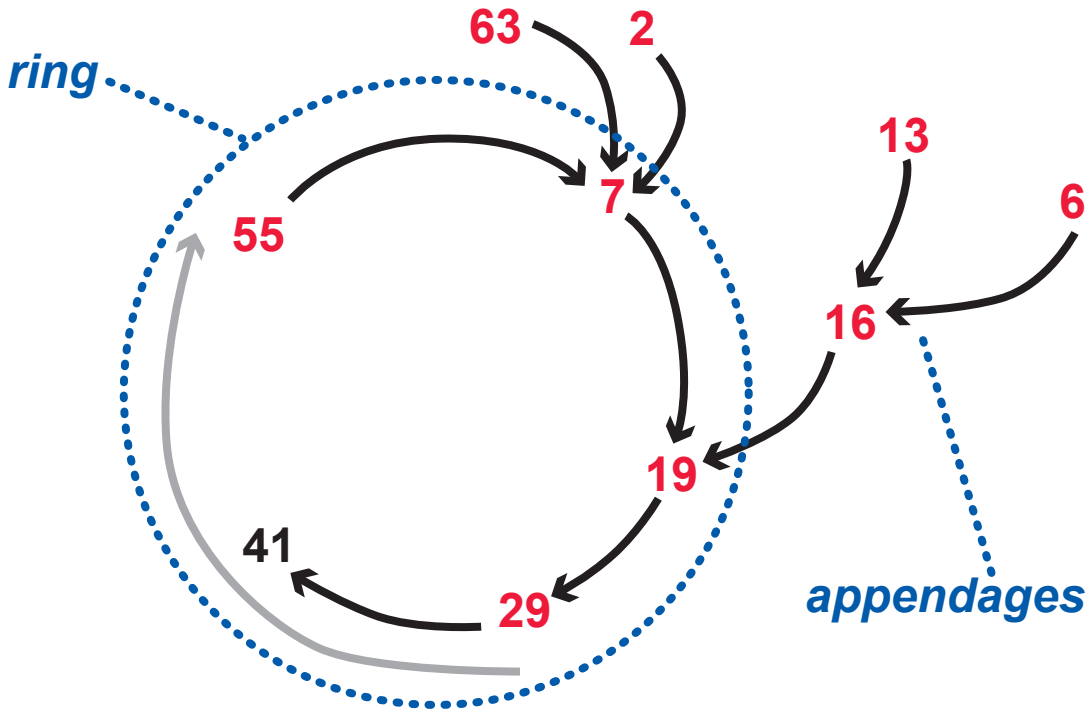
But if an ESL with L = 2 is . . .

. . . then 32 cannot fail!

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:

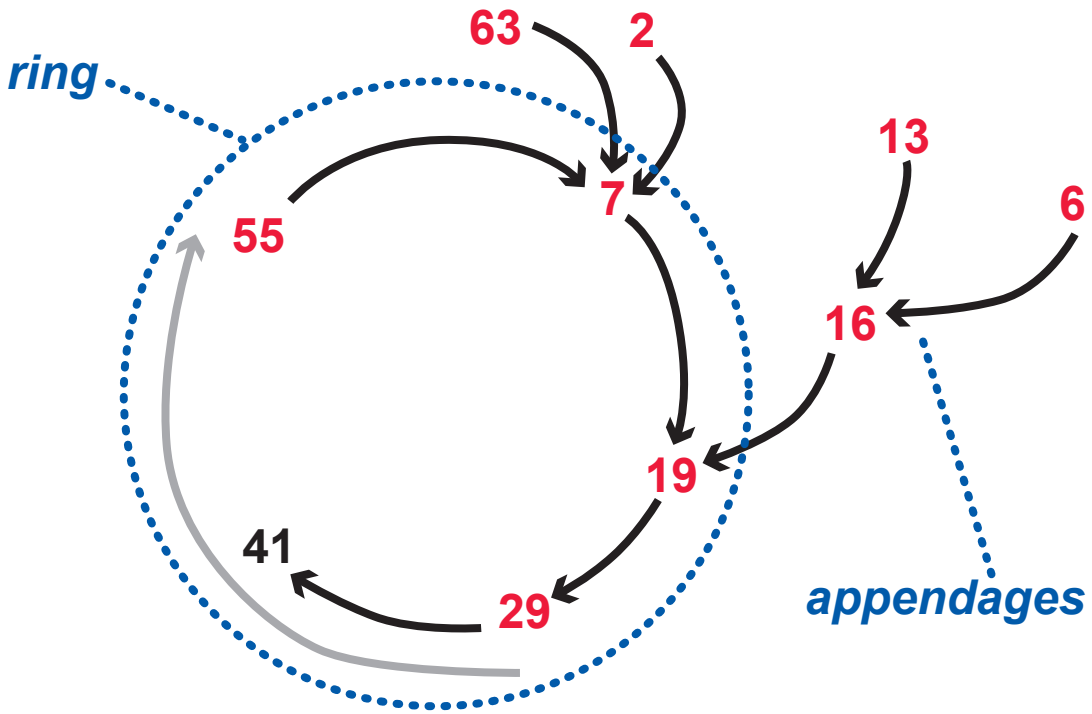
If a Chord network has the property *FullSuccessorLists*, then no failure leaves a member without a live successor.

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 . . .

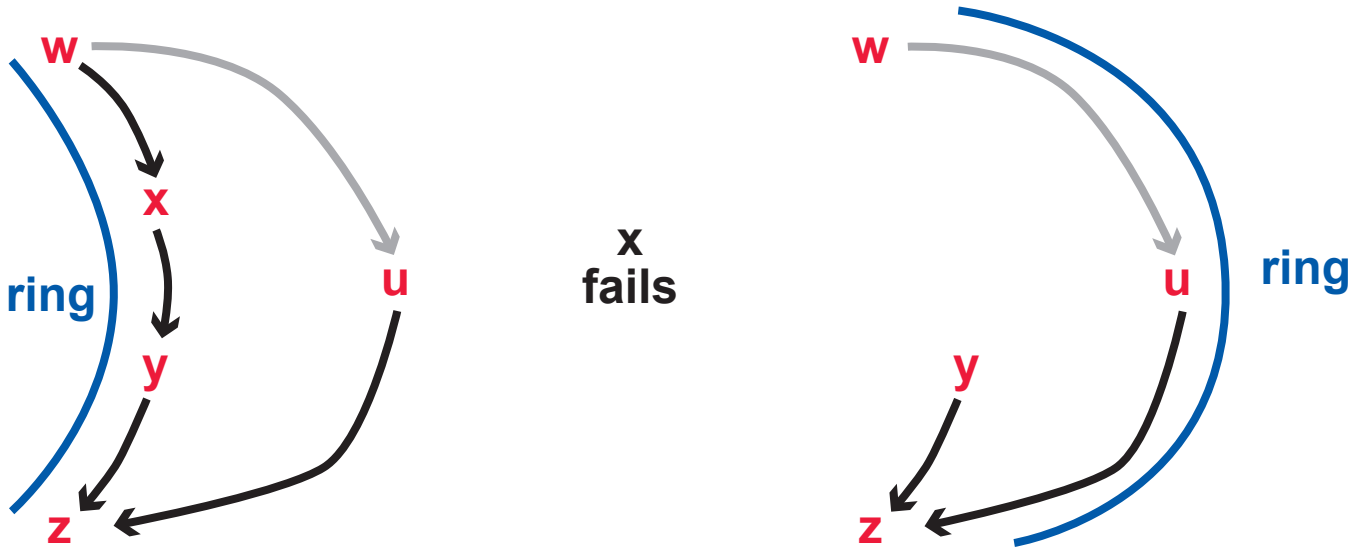
- there is a ring of best successors
- there is no more than one ring
- on the unique ring, the members are in identifier order

about the ring of best successors

- from each appendage member, the ring is reachable through 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:

this is just a formalization of the original operating assumption

OneLiveSuccessor

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

and SufficientPrincipals

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

THE PROOF OF CORRECTNESS:

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

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)

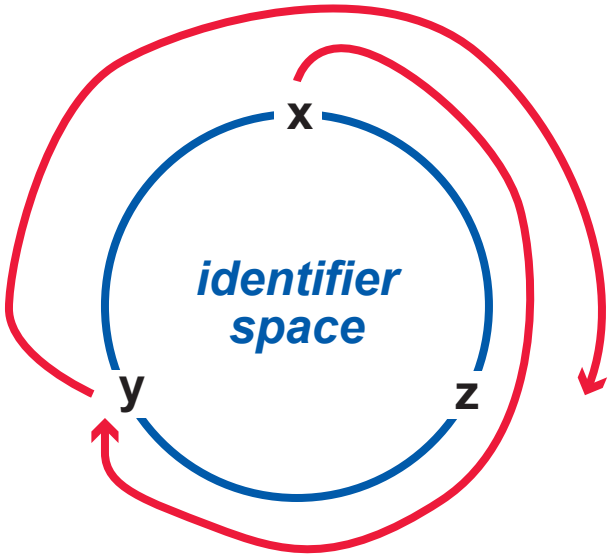
ORDERED (AND FULL) SUCCESSOR LISTS . . .

. . . 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, . . . y, . . . 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

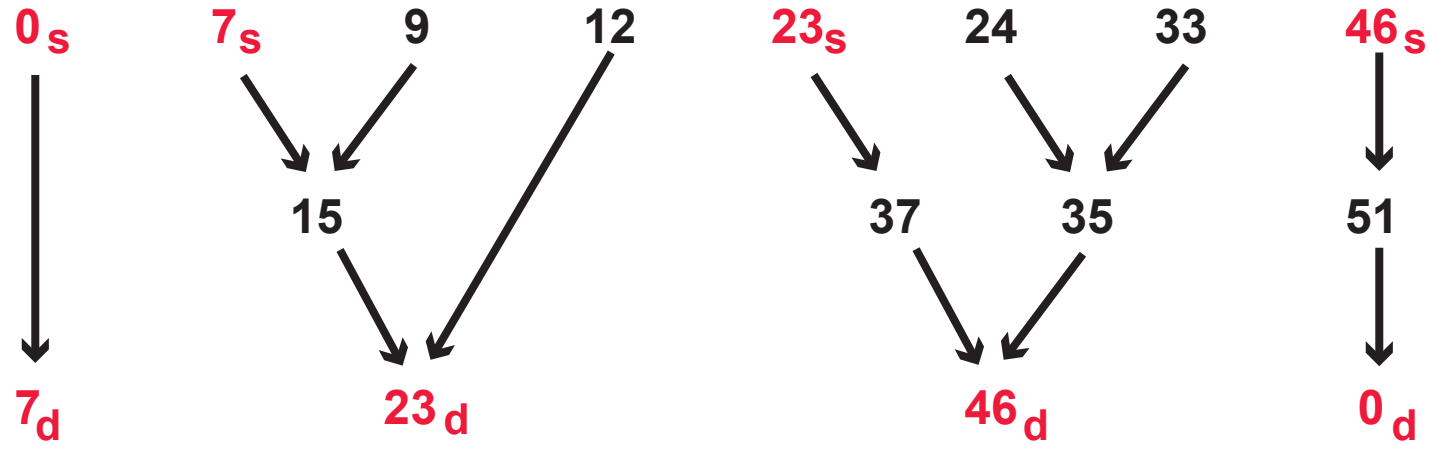
here is a graph of best successors:

these paths . . .

. . . do not skip principal nodes

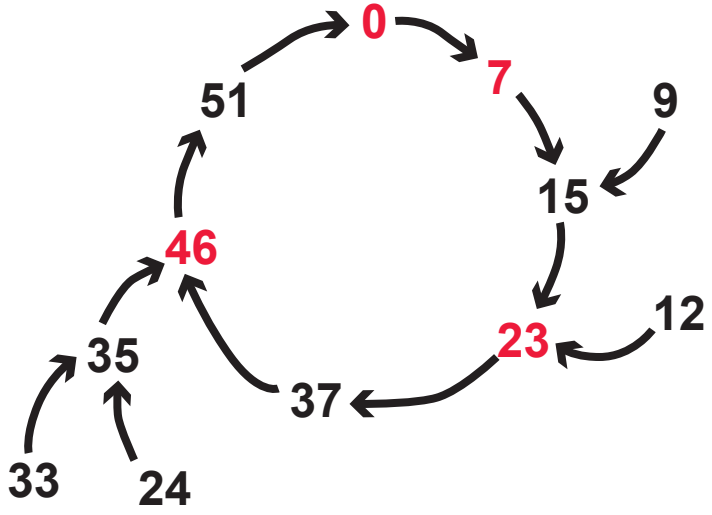
. . . are acyclic

. . . 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

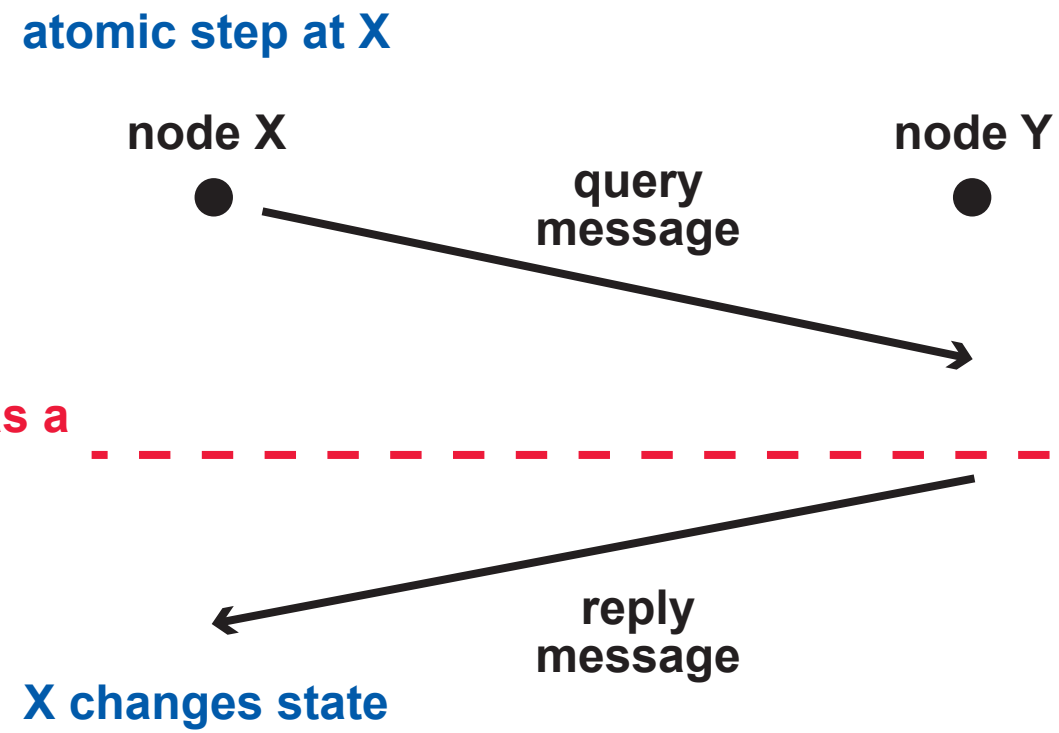


automatically satisfying *OneOrderedRing* and *Connected-Appendages*

CONCURRENCY AND COMMUNICATION

AN OPERATION IS A SEQUENCE OF ATOMIC STEPS

EACH ATOMIC STEP IS AN INTERNAL STATE CHANGE OR THIS:



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

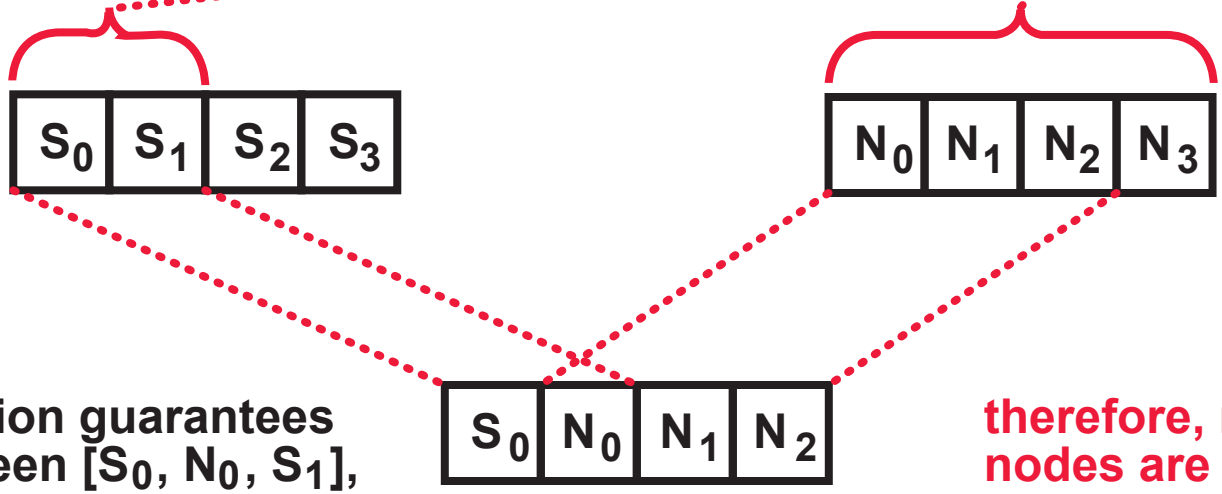
HOW STABILIZE PRESERVES THE INVARIANT

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**

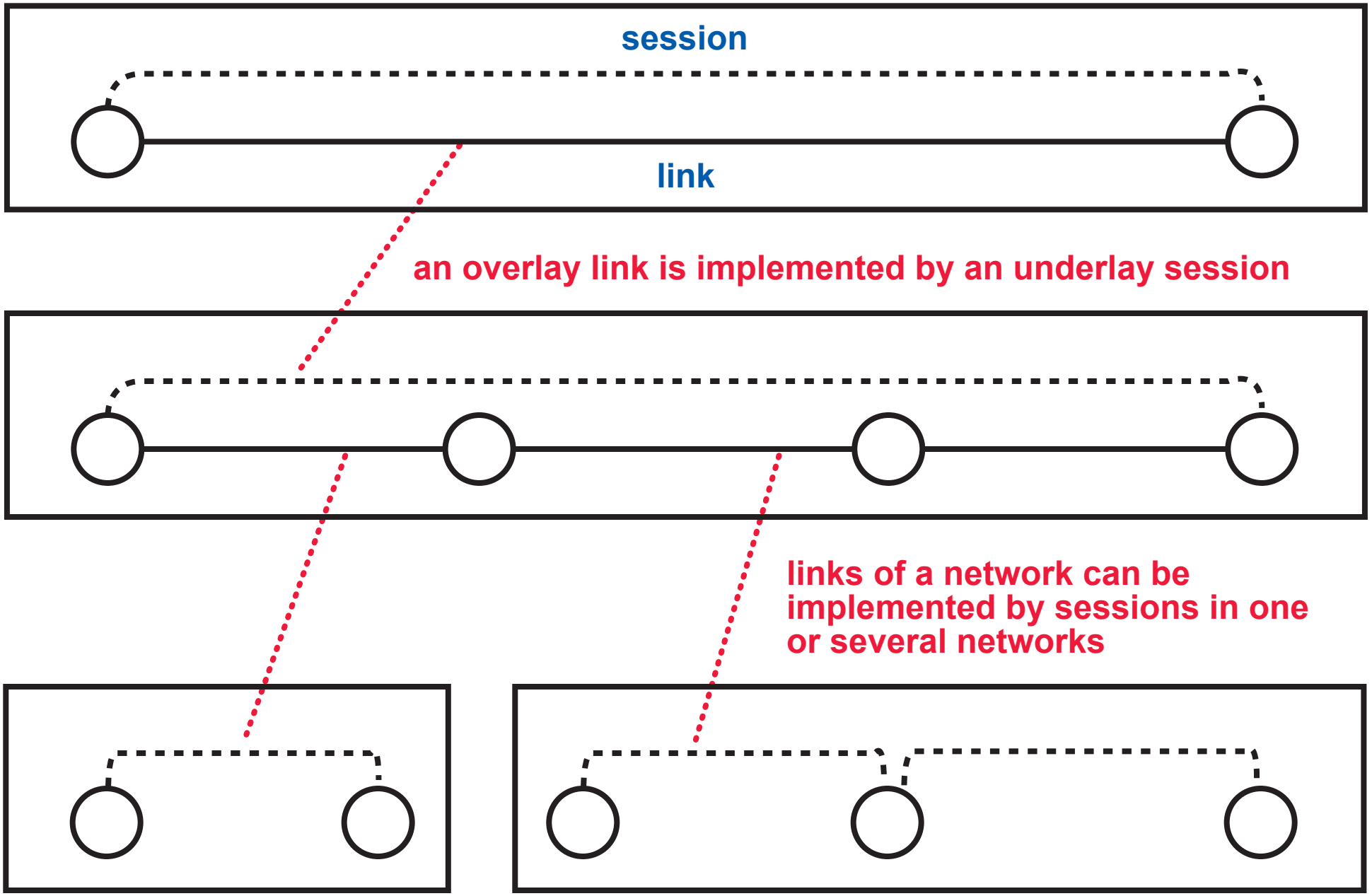
SECURITY SERVICES

- **data integrity**
- **packet filtering**

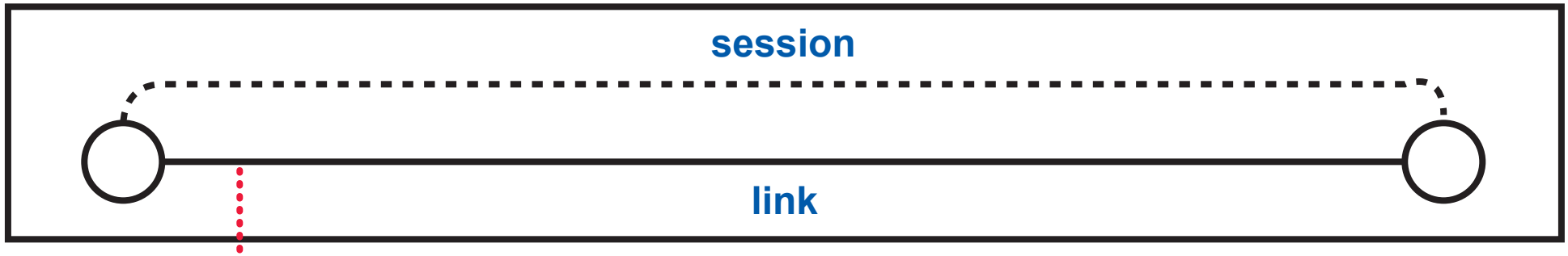
Simplifying Assumption:

There is no multihoming.

BASIC LAYERING



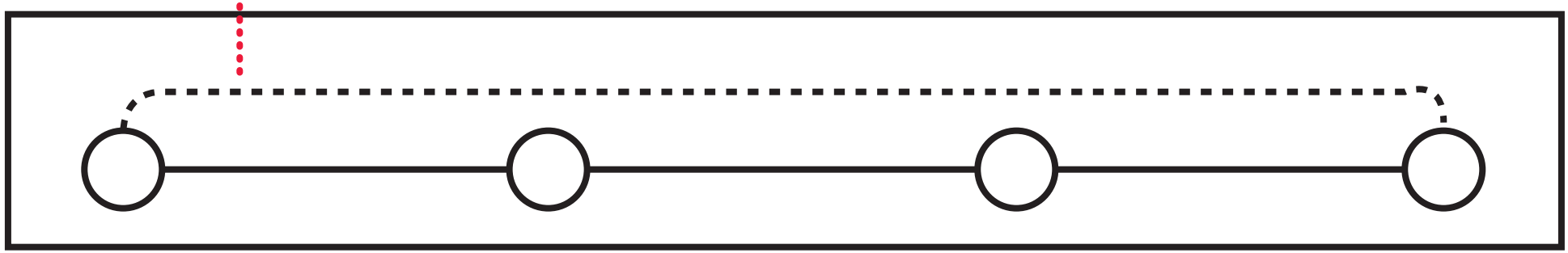
BEST-EFFORT POINT-TO-POINT SERVICE (QUANTIFIED)



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

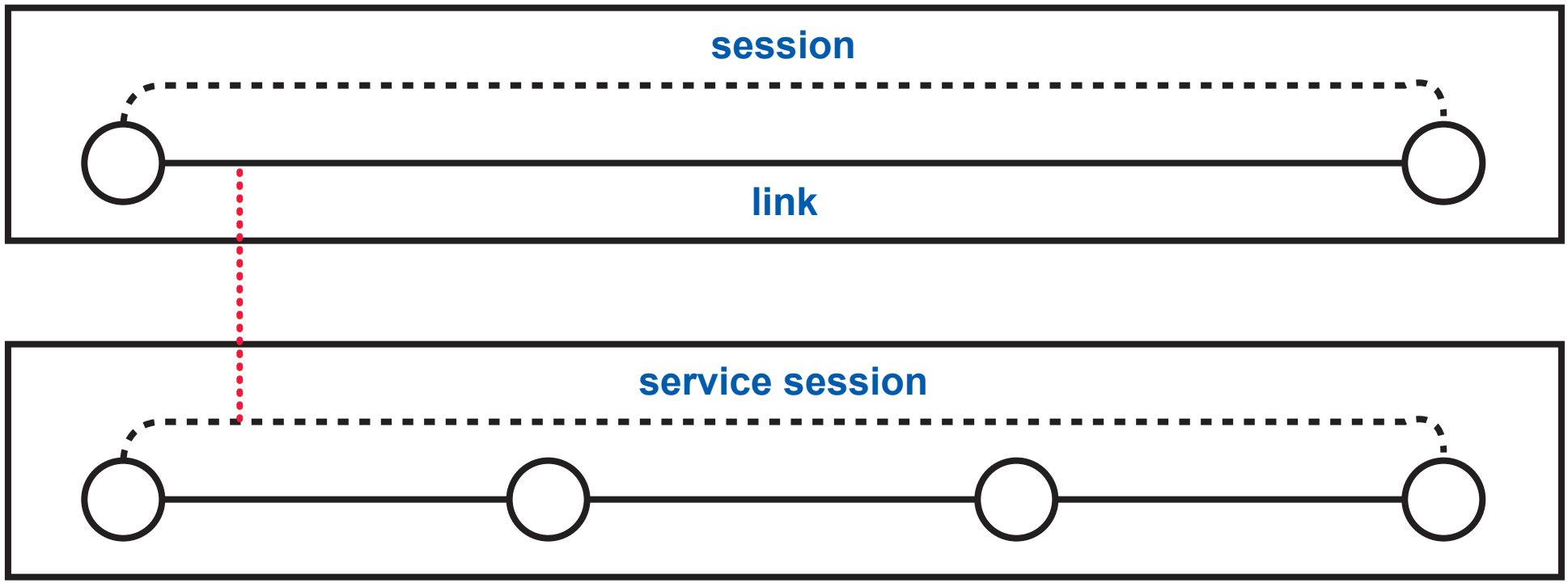


PRINCIPLES FOR LAYERING

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?



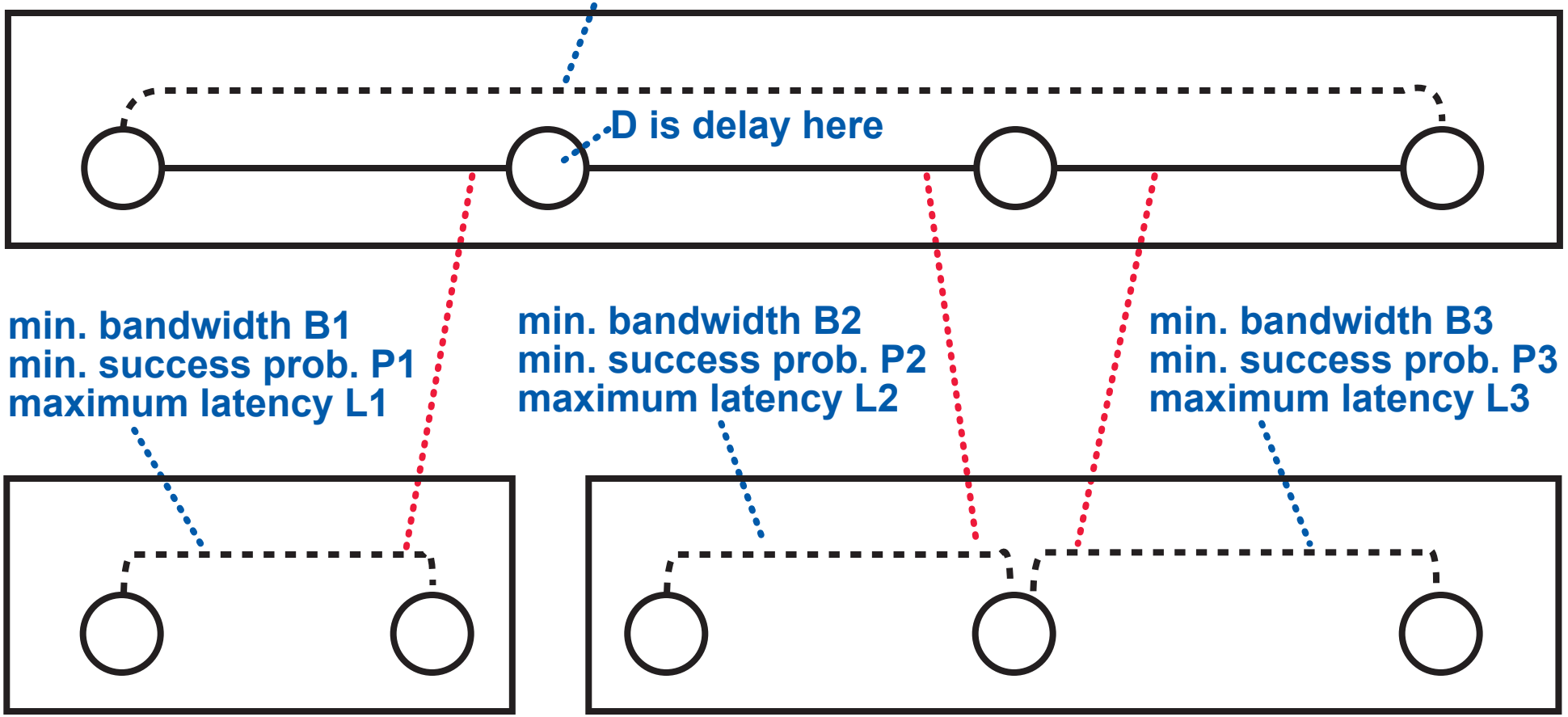
COMPOSITION OF "QUALITY OF SERVICE" SERVICE (QUANTIFIED SERVICE WITH GUARANTEES)

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

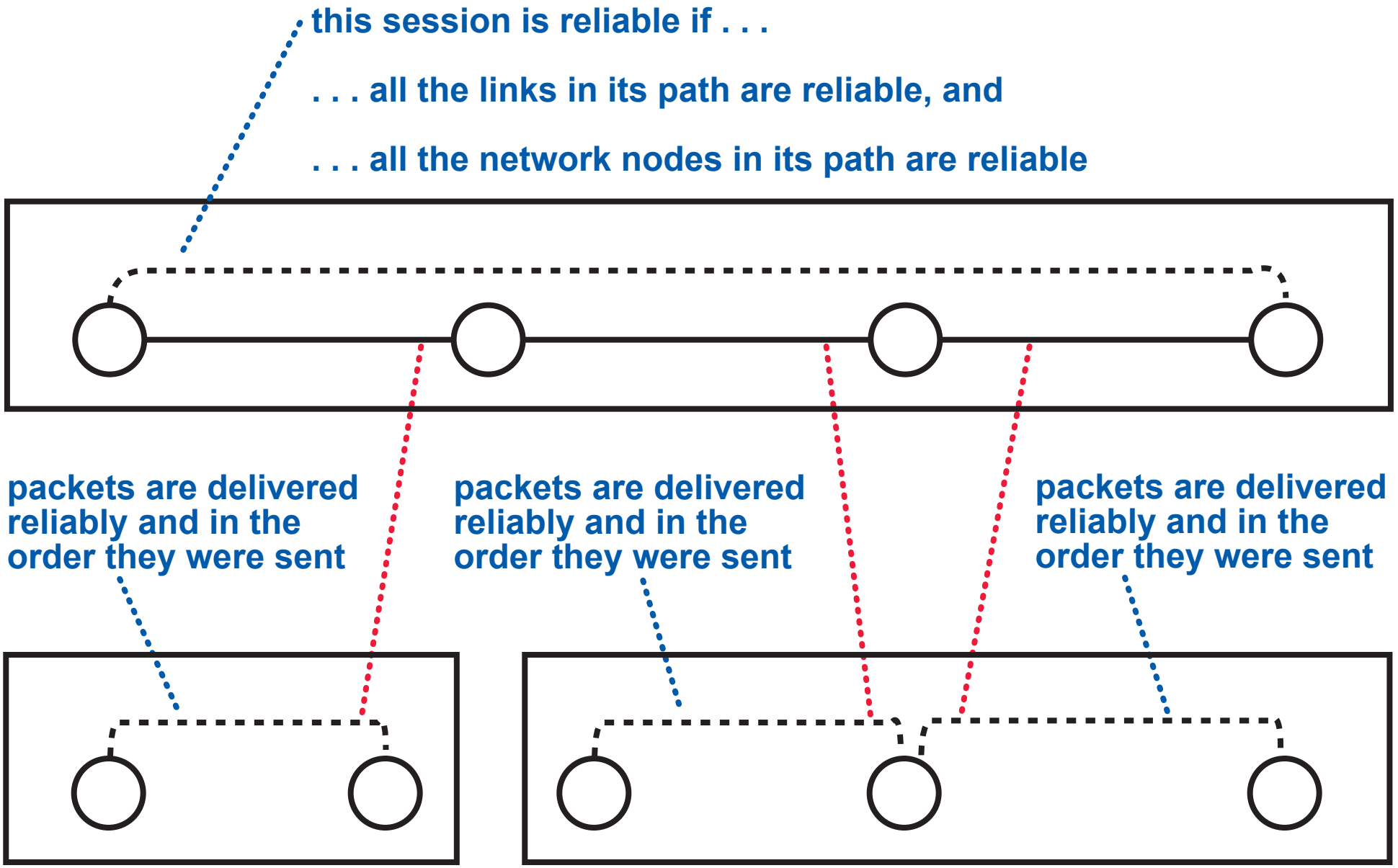
minimum bandwidth = minimum (Sj (Bj))
j

minimum success probability = product (Pj)
j

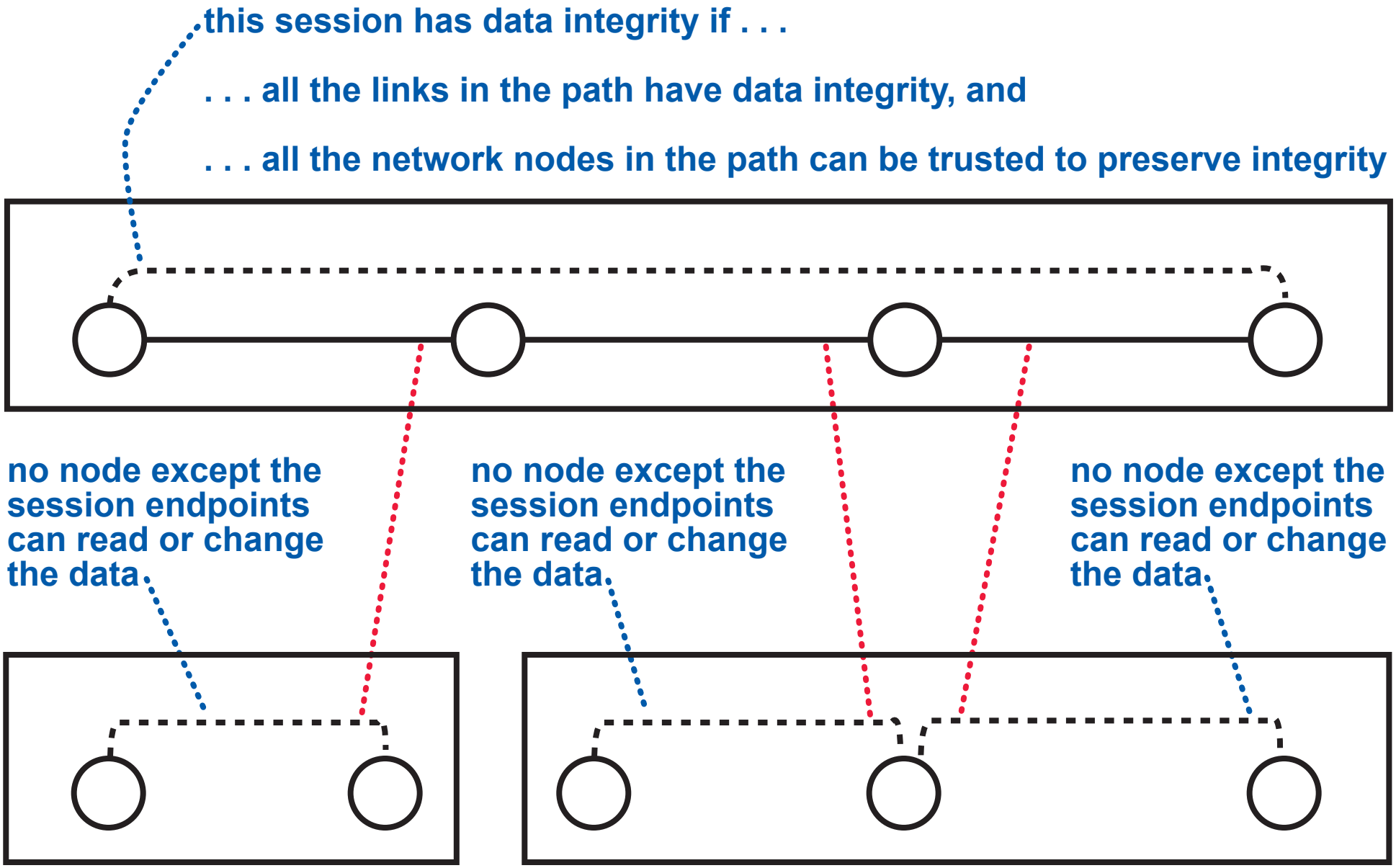
maximum latency = sum (Lj) + sum (Dj)
j j



COMPOSITION OF RELIABILITY SERVICE (FOR EXAMPLE, TCP)



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

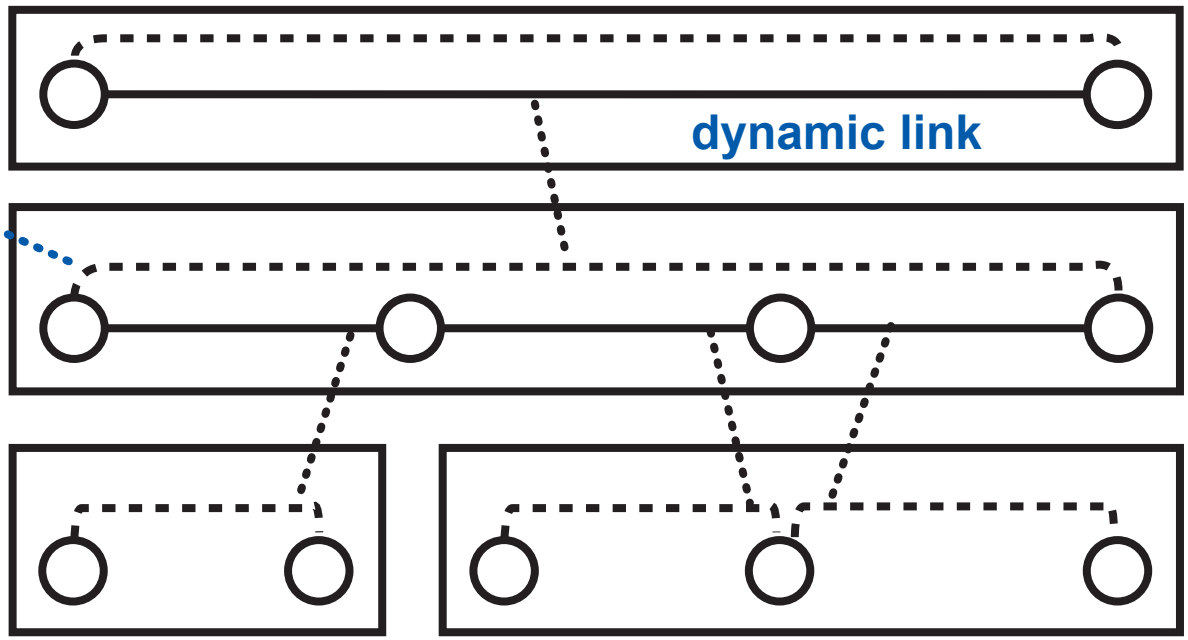


SERVICE	WHERE NEEDED?	WHERE IMPLEMEN-TABLE?	HOW PROPA-GATED?	RESULT?
QoS	top session	where a network can provide sessions with dedicated paths, shorter paths, higher-quality paths, etc.	piecewise	must propagate up to BE2EUS
reliability	top session	any session protocol	piecewise	put in BE2ES or above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

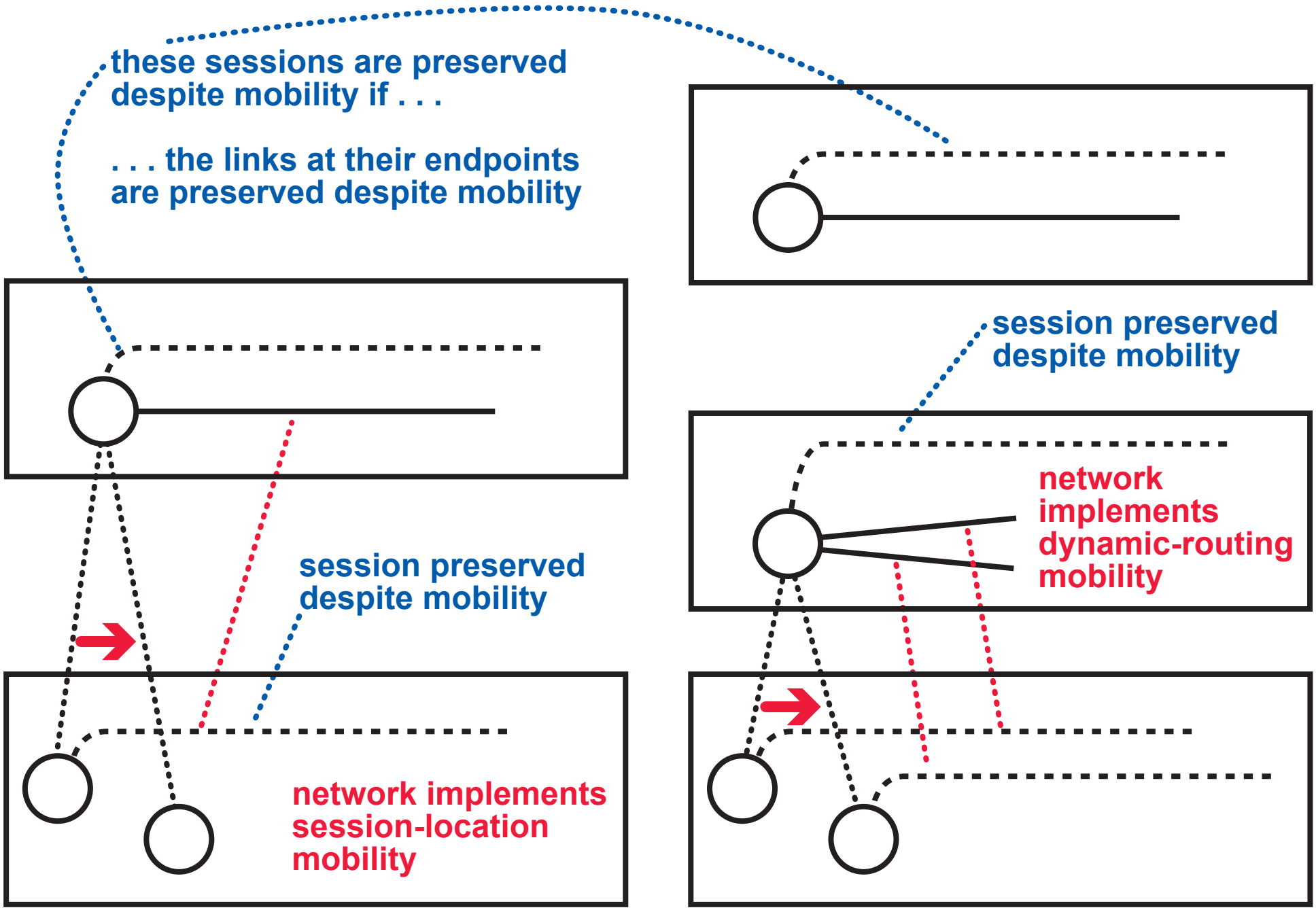
bottom end-to-end unshared session (BE2EUS)

all properties of this session propagate piecewise to the top

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



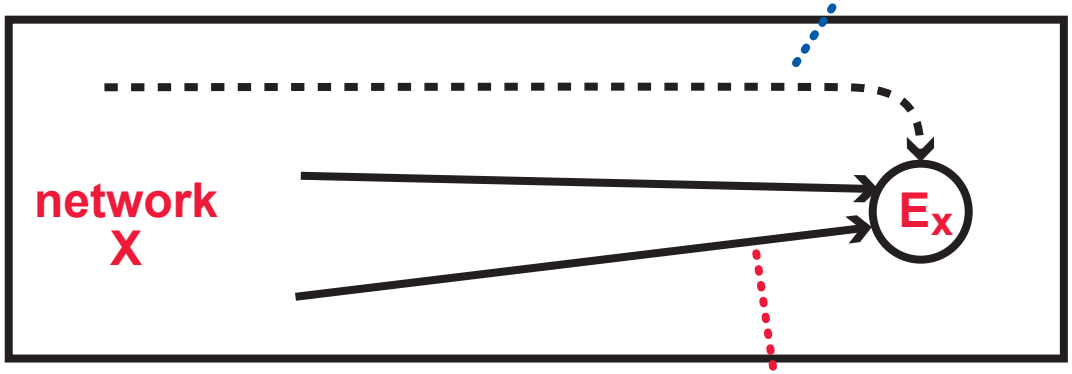
COMPOSITION OF MOBILITY SERVICE



COMPOSITION OF PACKET-FILTERING SERVICE

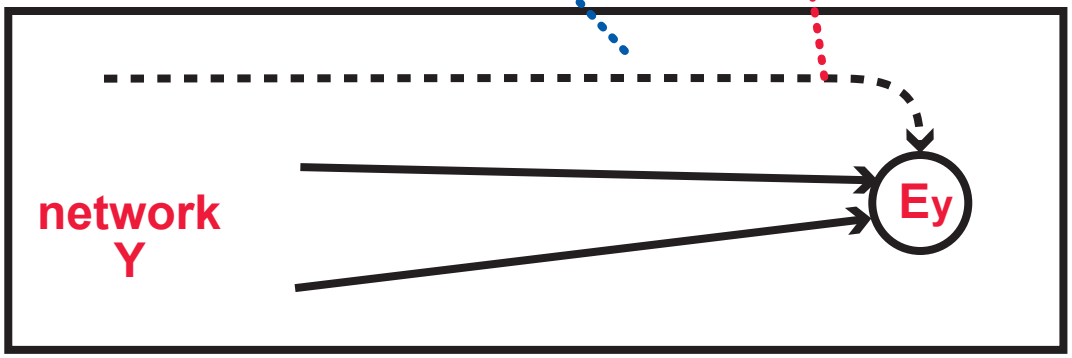
member receives no undesirable session-initiation packets if . . .

. . . 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 IMPLEMEN-TABLE?	HOW PROPA-GATED?	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

SERVICE INTERACTIONS

	QoS
RELIABILITY	reliability converts bandwidth, probability, latency to goodput, which also propagates piecewise
INTEGRITY	encryption decreases bandwidth and increases latency, both bad
MOBILITY	
PACKET FILTERING	filtering increases latency (bad) and bandwidth (good)

	RELIABILITY	INTEGRITY (ENCRYPTION)	MOBILITY
INTEGRITY	reliability above encryption		
MOBILITY	reliability above mobility	encryption above mobility	
PACKET FILTERING		filtering and encryption are independent only if session initiations are not encrypted	filtering above mobility or far from endpoint