HOW TO MAKE CHORD CORRECT

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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

m = 6

successor

successor2

predecessor

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

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

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

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)
- data replication and consistency of replicated data
- enhanced queries
an operation changes the state of one member

most operations are scheduled, asynchronously and autonomously, by their own nodes

now 10 is fully integrated into the ring
MORE OPERATIONS OF THE PROTOCOL

22 FAILS OR LEAVES

22 has no pointers, does not respond to queries

16 UPDATES

35 FLUSHES

9 RECONCILES

now the hole left by 22 is repaired
IN A VALID NETWORK . . .

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

WHAT THE PROTOCOL SHOULD DO

**Theorem:**
A Chord network is always Valid.

**Theorem:**
In any execution state, if there are no subsequent join or fail events, eventually all pointers will become globally correct and remain globally correct.

“eventual consistency”

WHAT THE PROTOCOL CANNOT DO

**Well-Known Fact:**
If a Chord network is not Valid, then some member nodes are unreachable from some other nodes, . . .

. . . and this cannot be repaired.
Because of sloppy, informal specification and proof . . .

. . . of the seven properties claimed to be invariants, not one is actually an invariant.

including the four clauses of Valid

OrderedMerges . . .

. . . means that appendages merge in the correct places, as they do here

OrderedMerges is easily violated

VIOLATIONS OF OrderedMerges

- are not incorrect
- cause some lookups to fail
- invalidate some assumptions used in performance analysis
- can be demonstrated in Chord networks with 3 nodes

how could they go unknown for ten years?

this is why formal methods are so important
OUTLINE

HOW TO MAKE CHORD CORRECT

- fixing the protocol
- the elusive inductive invariant
- proof of correctness

THE ROLE OF FORMAL METHODS

COMMUNITY REACTIONS
Node 3 had no successor yet (it is not required to have all successors filled in).

When it stabilized, it replaced a pointer to a live node (40) with a pointer to a dead node (16).

Now Node 3 has no pointers to live nodes, and there is no ring.
The Bug in Initialization

In Original Chord, a network is initialized with one member.

- The length of the successor list is $R = 2$.
- First and second successors must duplicate each other.

Stabilizes, rectifies

One failure is allowed by operating assumptions . . .

. . . but the member nodes, having only one distinct entry in their successor lists, cannot recover from this failure.
Definition: A Chord network has the property \textit{FullSuccessorLists} if the extended successor list of each member has \( R+1 \) distinct entries.

Operating Assumption (a kind of fairness):

If a Chord network has the property \textit{FullSuccessorLists}, then every member has a best successor.

ultimately, this relates the failure rate to the rate of stabilization
FIXING ORIGINAL CHORD

FIXING THE OPERATIONS

- merge small, independently scheduled operations into bigger ones

  join + reconcile = JOIN

  stabilize + reconcile + update = STABILIZE

  notified + flush = RECTIFY

  this populates successor lists
  more eagerly,
  keeping them fuller

- check that a new pointer is live before replacing another pointer with it

- write complete, precise pseudocode

- be explicit about inter-node communication (queries)

FIX INITIALIZATION

- alter the initialization to satisfy FullSuccessorLists with all successors live

  this requires a minimum of $R + 1$ members
WHAT IS THE INDUCTIVE INVARIANT?

NECESSARY BUT NOT SUFFICIENT:

- 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

NOT INARIANT (EVEN IN CONJUNCTION WITH THE ABOVE):

- FullSuccessorLists
- OrderedSuccessorLists
- and many, many other well-motivated candidates!

For all contiguous sublists \([x, y, z]\) in an extended successor list, Between \([x, y, z]\).
WHY IS IT SO DIFFICULT?

THE 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

. . . BUT “RING VERSUS APPENDAGE” IS CONTEXT-DEPENDENT AND FLUID:
A TRIAL INDUCTIVE INVARIANT

Valid and NoDuplicates and OrderedSuccessorLists

EXCLUDES this extended successor list (R = 2):

[3, 4, 4]...........same first and second successors

[3, 7, 5]...........list is not in numerical order

this network satisfies the property

now the identifiers in the ring are out of order, so the trial invariant is false
THE INDUCTIVE INARIANT

Definition by example:
If 48 is a member, this extended successor list skips it.

\[45 \ 47 \ 55\]

ANOTHER OPERATING ASSUMPTION:
A Chord network has a stable base of R+1 nodes that are always members.

THE INDUCTIVE INVARIANT:
OneOrderedRing
and ConnectedAppendages
and BaseNotSkipped

no extended successor list skips a member of the stable base
WHY THE INDUCTIVE INVARIANT IS SUFFICIENT

ANOTHER OPERATING ASSUMPTION:

A Chord network has a stable base of R+1 nodes that are always members.

THE INDUCTIVE INVARIANT:

OneOrderedRing and ConnectedAppendages and BaseNotSkipped

this applies to ring members and appendages alike

One case of a proof that this invariant implies OrderedSuccessorLists:

If \([x,y,z]\) appears in a successor list and the values are as pictured, OSL is false.

But there can be no base member between \(x\) and \(y\) . . .

. . . and no base member between \(y\) and \(z\) . . .

. . . so \(y\) is the only possible base member, which is a contradiction.
SIGNIFICANCE OF THE BASE

WHAT DOES THE STABLE BASE DO, IN PRACTICE?

A stable base would have 3-6 members,

... while a Chord network can have millions of nodes, most of which are nowhere near a base node,

... so how can their operations be affected by the stable base?

CONCLUSIONS

- The purpose of the stable base is to prevent anomalies in small networks.

- Once a Chord network has grown to a sufficient size, a stable base is not needed!

this matters because each member must be a high-availability node (cluster) with a fixed IP address

duplicate entries in successor lists, successor lists that “wrap around” and become disordered, etc.

this does not mean that a large network cannot have flaws!

the large network must have grown from a small network satisfying the invariant
PROOF OUTLINE

THEOREM: In any reachable state, if there are no subsequent joins or failures, then eventually the network will become ideal and remain ideal.

PROOF:

1. Show that the inductive invariant is true of all reachable states.
   AUTOMATED (exhaustive search over a finite domain)

2. An operation that takes 0 or 1 query can be considered atomic. For operations that take 2 queries, show that the first half and the second half can safely be separated by concurrent operations.
   AUTOMATED

3. An effective repair operation is one that changes the network state. Define a natural-valued measure of the error in the network, and show that every effective repair operation decreases the error.
   MANUAL

4. Show that whenever the network is not Ideal, some effective repair operation is enabled.

5. Show that whenever the network is Ideal, no effective repair operation is enabled.
   AUTOMATED
   because the error is finite, after a finite number of repairs, the network will have no error and be Ideal
   AUTOMATED
   once it is ideal it stays ideal, because repair operations will not change it
SMALL SCOPE HYPOTHESIS

NETWORK SIZE

We can only do exhaustive search for networks up to some node size \( N \).

The “small scope hypothesis” makes explicit a folk theorem that most real bugs have small counterexamples.

Well-supported by experience, it is the philosophical basis of lightweight modeling and analysis.

RING STRUCTURES

The hypothesis is especially credible in this study, because ring structures are so symmetrical.

For example, to verify assertions relating pairs of nodes, it is only necessary to check rings of up to size 4.

not directly relevant to Chord

EXPLORATION OF CHORD MODELS CONFIRMS THIS

Original version of Chord was explored with \( R = 2 \).

new counterexamples were found at \( N = 2, 3, 4 \) (many of each), and 5 (just one)

Nearly-correct versions of Chord were explored with \( R = 2 \).

new counterexamples were found at \( N = 4, 5 \) (many of each), and 6 (just one)

Correct version of Chord was explored with \( R = 3 \).

no new counterexamples

WHAT SCOPE IS BIG ENOUGH?

I feel very safe having analyzed up to \( R = 3 \) and \( N = 9 \).
OUTLINE

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THE ROLE OF FORMAL METHODS

COMMUNITY REACTIONS
LIGHTWEIGHT MODELING

**DEFINITION**

- constructing a small, abstract logical model of the key concepts of a system
- analyzing the properties of the model with a tool that performs exhaustive enumeration over a bounded domain

**WHY IS IT "LIGHTWEIGHT"?**

- because the model is very abstract in comparison to a real implementation, it is small and can be constructed quickly
- because the analysis tool is "push-button", it yields results with relatively little effort

**MY FAVORITE TOOLS**

**ALLOY**

- Alloy language combines relational algebra, first-order predicate calculus, and transitive closure
- Alloy Analyzer compiles a bounded model into Boolean constraints, uses SAT solvers to decide whether the constraints are satisfiable

**SPIN**

- Promela is a simple programming language with concurrent processes, messages, bounded message queues, and fixed-size arrays
- Spin is a model-checker: the program specifies a large finite-state machine that the checker explores exhaustively

*in contrast, theorem proving is not “push-button”*
What is easy

It is easy to model Chord in either Alloy or Promela.

It is easy to . . .

- find bugs
- check assertions
- get counterexamples to assertions

. . . in networks with up to 4 nodes.

with $R = 2$, this covers a lot of ground

What is very hard

To prove that Chord is correct, we need an inductive invariant (Valid is not strong enough).

We don’t know if there is an inductive invariant, or if there is one, what it is.

Without an inductive invariant, the value of analysis is limited.

There are many trial invariants, some straightforward and some baroque, and none of them seem to work.
all the states explored are true, reachable states
traces can be long, even infinite

HOWEVER, only networks with 4-5 nodes can be analyzed completely, and this is not enough
“REAL” VERIFICATION VERSUS BOUNDED ANALYSIS

“Why don’t you do a real proof (for arbitrary R and N)?”

**ANSWER # 1**

- I don’t think engineers will do “real” proofs with theorem provers.
- I think that engineers can and should do lightweight modeling and analysis, and I am trying to persuade them of its value.

**ANSWER # 2**

- I don’t know how (but I’m trying).
- A real proof would be very illuminating!
Chord is interesting to two subfields of computer science

The Reaction: Networking

... most of these problems were easy to find with a small model and the Alloy Analyzer,

... so there is an important lesson about lightweight formal modeling as a design tool,

... but the networking community rejects papers on fixing Chord

The Reaction: Distributed Systems

- Amazon Web Services credits this work with overcoming their bias against formal methods, and causing them to start using formal methods to find bugs

- AWS is now using TLA, with great success
REFERENCES

CHORD WORK

“Using lightweight modeling to understand Chord”

*ACM SIGCOMM Computer Communications Review, April 2012*

“A practical comparison of Alloy and Spin”

*Formal Aspects of Computing, 2014*

“How to make Chord correct”

*arXiv, submitted for publication*

AMAZON

“How Amazon Web Services uses formal methods”

*Chris Newcombe et al. Communications of the ACM, April 2015*

ALL PAPERS AND MODELS

COMMUNITY REACTIONS

DISTRIBUTED-COMPUTING COMMUNITY IS EMBRACING FORMAL METHODS

Amazon credits this work with giving them the required evidence that formal methods work on real-world systems; Amazon now uses formal methods routinely.

SIGCOMM COMMUNITY IS CREATIVE IN REJECTING FORMAL METHODS

“these flaws are obvious and implementers fix them”

- this is patently false
- even if it were true, why should each implementer have to rediscover them?

“these flaws are improbable and do not occur in real executions”

- how can anyone know that?

- computing execution probabilities would require implementation-specific information such a timing
- there are Chord failures (hearsay), and no one knows the cause of all of them

note that Chord could use more capabilities and stronger properties, so people build on the basic protocol

- extensions should not be verified on an unsound foundation
- note that people do not really understand how Chord works (incorrect invariants and performance analyses)

- the modeling, analysis, invariant, and proof all contribute to insight
- dynamically checking the invariant is a good security principle, but cannot be done if the invariant is not known