P2: Implementing Declarative Overlays

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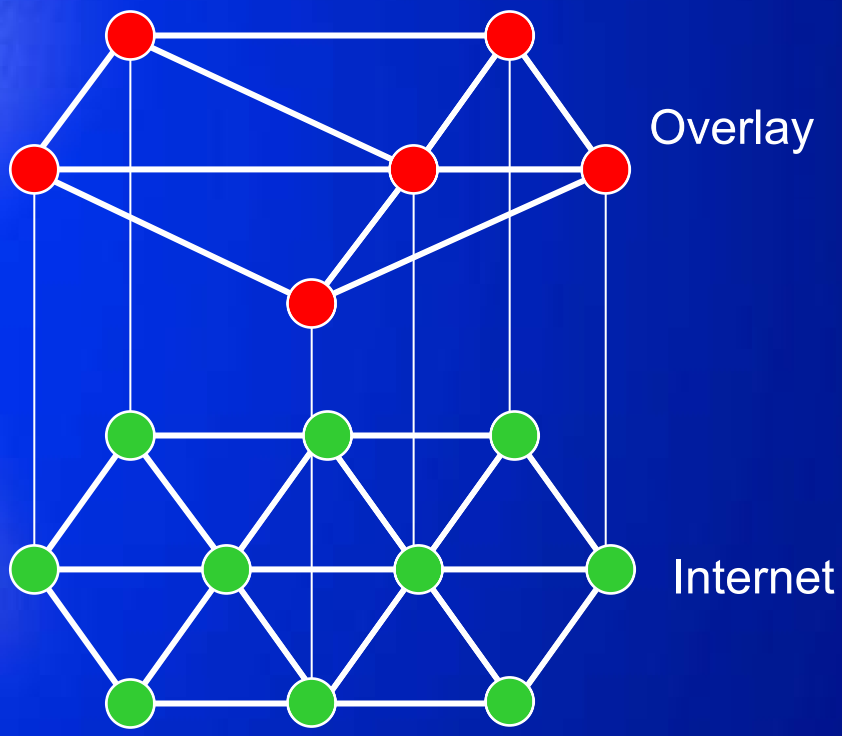
Overlays: a broad view

"Overlay": the routing and message forwarding component of *any* non-trivial distributed system



Overlays Everywhere…

- Many examples:
  - Internet Routing, multicast
  - Content delivery, file sharing, DHTs, Google
  - Microsoft Exchange
  - You don't like Internet Routing? Make up your own rules (RON)
  - Paranoid? Run Freenet
  - Intrusion detection with friends (DDI, Polygraph)
  - Have your assets discover each other (iAMT)

Distributed systems innovation *needs* overlays

If only it weren't so hard

- In theory
  - Figure out right properties
  - Get the algorithms and protocols
  - Debug them
  - Repeat
- But in practice
  - No global view
  - Wrong choice of algorithms
  - Impaired introspection
  - Homicidal boredom
  - Next to no debug support

It's hard enough as it is
Do I also need to reinvent the wheel every time?

Our Goal

- Make network development more accessible to developers of distributed applications
  - Specify network at a high-level
  - Automatically translate specification into executable
  - Hide everything they don’t want to touch
  - Enjoy performance that is *good enough*
- Do for networked systems what SQL and the relational model did for databases

The argument:

- The set of routing tables in a network represents a *distributed data structure*
- The data structure is characterized by a set of ideal *properties* which define the network
  - Thinking in terms of structure, not protocol
- *Routing* is the process of maintaining these properties in the face of changing ground facts
  - Failures, topology changes, load, policy…

Routing as Query Processing

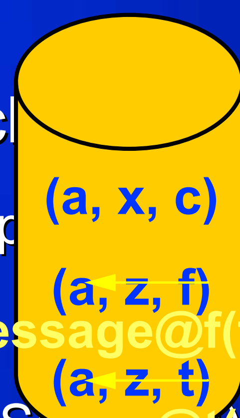
- In database terms, the routing table is a *view* over changing network conditions and state
- Maintaining it is the domain of distributed continuous query processing
- Not merely an analogy:
  We have ***implemented*** a general routing protocol engine as a query processor.

Two directions

1. Declarative expression of Internet Routing protocols
   - Loo et. al., ACM SIGCOMM 2005
2. Declarative *implementation* of overlay networks
   - Loo et. al., ACM SOSP 2005
   - The focus of this talk (and my work)

P2: A Declarative Overlay Engine

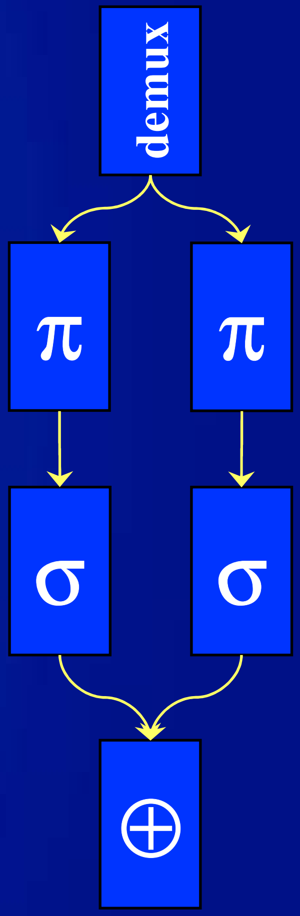
- Distributed state
  - Distributed soft state in relational tables, holding tuples of values
    - route (S, D, H)
  - Non-stored information passes around as *event tuple streams*
    - message (X, D)
- Overlay specification in declarative logic language (OverLog)
  - <head> :- <precondition1>, <precondition2>, … , <preconditionN>.
  - Location specifiers @X *place* tuples at specific nodes
  - message@H(H, D) :- route@S(S, H), message@S(S, D).



P2 Dataflow

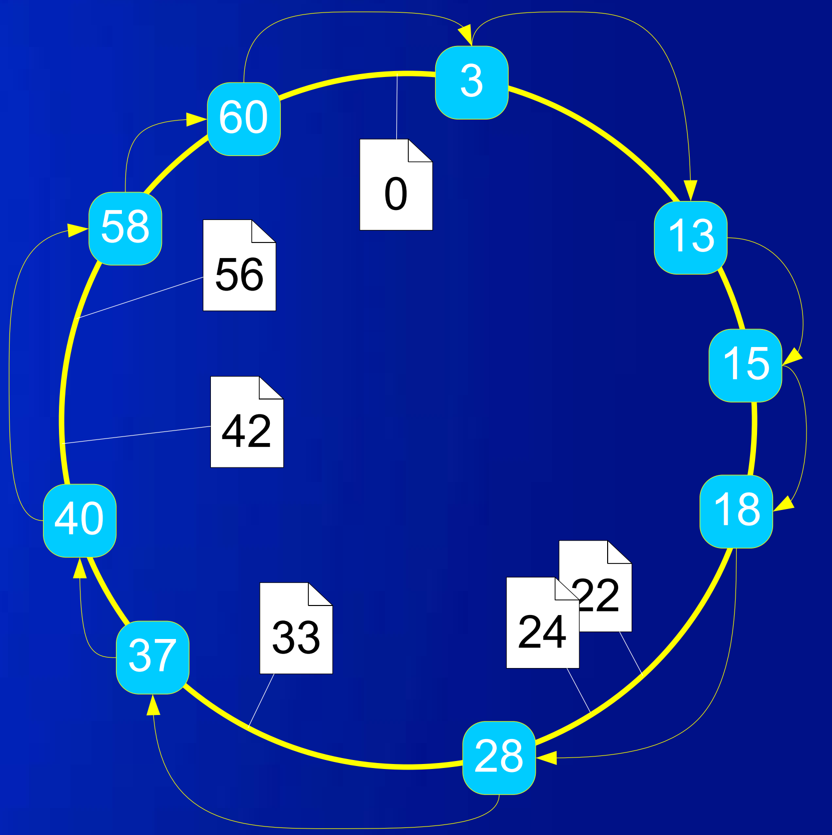
- Overlog automatically translated to dataflow graph
  - C++ dataflow elements (similar to Click elements)
  - Implements:
    - relational operators (joins, selections, projections)
    - flow operators (multiplexers, demultiplexers, queues)
    - network operators (congestion control, retry, rate limits)
  - Interlinked via asynchronous push or pull typed flows
- Engine executes dataflow graph at runtime

A distributed query processor to maintain overlays



Example: Ring Routing

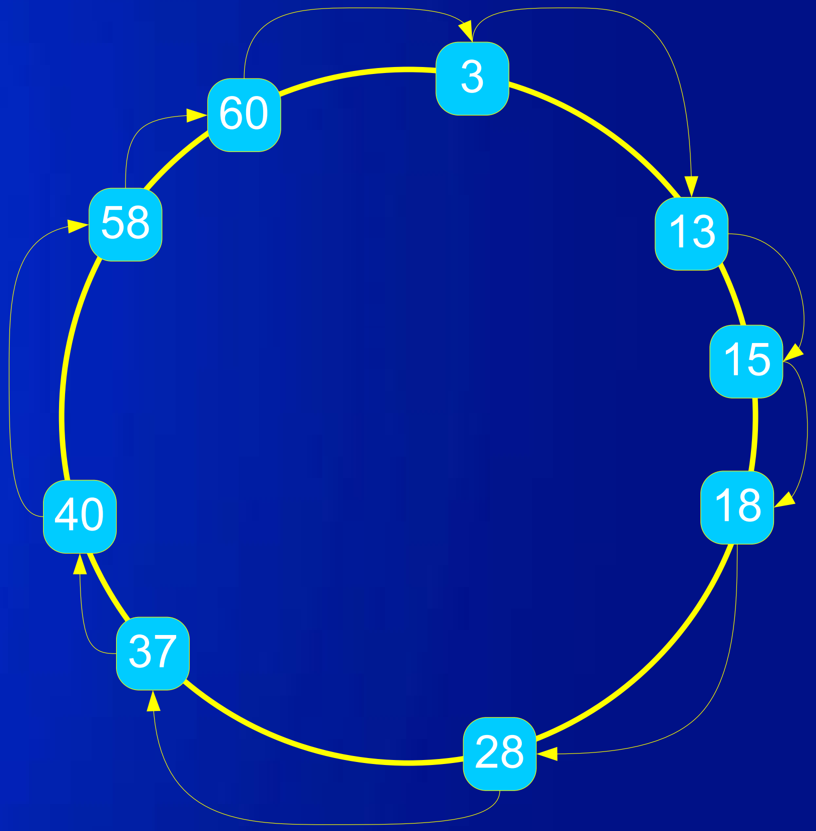
- Every node has an *address* (e.g., IP address) and an *identifier* (large random)
- Every object has an *identifier*
- Order nodes and objects into a ring by their identifiers
- Objects “served” by their successor node
- Every node knows its *successor* on the ring
- To find object *K*, walk around the ring until I locate K’s immediate successor node



Example: Ring Routing

- How do I find the responsible node for a given key k?
- n.lookup(k)

```
if k in (n, n.successor)
    return n.successor
else
    return n.successor. lookup(k)
```



Ring State

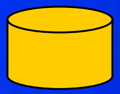
- n.lookup(k)

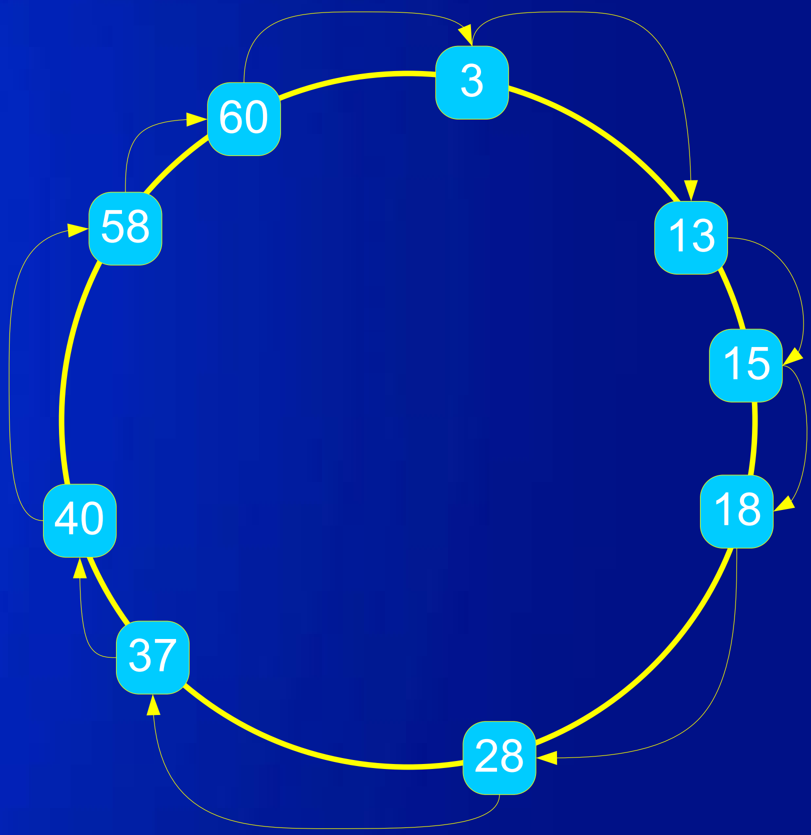
  if k in (n, n.successor)

  return n.successor

  else

  return n.successor. lookup(k)

- Node state tuples
  - node(NAddr, N) 
  - successor(NAddr, Succ, SAddr)
- Transient event tuples →
  - lookup (NAddr, Req, K)



Pseudocode to OverLog

- <u>n.lookup(k)</u>

  if k in (n, n.successor]

  return n.successor

  else

  return n.successor. lookup(k)

- Node state tuples
  - node(NAddr, N)
  - successor(NAddr, Succ, SAddr)
- Transient event tuples
  - lookup (NAddr, Req, K)

```
response@Req (Req, K, SAddr) :-
        lookup@NAddr (NAddr, Req, K),
        node (NAddr, N),
        succ (NAddr, Succ, SAddr),
        K in (N, Succ].
```

Pseudocode to OverLog

- n.lookup(k)

  if k in (n, n.successor]

  return n.successor

  else

  return n.successor. lookup(k)
- Node state tuples
  - Node (NAddr, N)
  - Successor NAddr, Succ, SAddr)
- Transient event tuples →
  - lookup (NAddr, Req, K)

```
response@Req (Req, K, SAddr) :-
        lookup@NAddr (NAddr, Req, K),
        node (NAddr, N),
        succ (NAddr, Succ, SAddr),
        K in (N, Succ].

lookup@SAddr (SAddr, Req, K) :-
        lookup@NAddr (NAddr, Req, K),
        node (NAddr, N),
        succ (NAddr, Succ, SAddr),
        K not in (N, Succ].
```

Location Specifiers

- n.lookup(k)

  if k in (n, n.successor]

  return n.successor

  else

  return n.successor. lookup(k)

- Node state tuples
  - node(NAddr, N)
  - successor(NAddr, Succ, SAddr)
- Transient event tuples
  - lookup (NAddr, Req, K)

R1 response@Req(Req, K, SAddr) :-

lookup@NAddr(NAddr, Req, K),

node@NAddr(NAddr, N),

succ@NAddr(NAddr, Succ, SAddr),

K in (N, Succ].

R2 lookup@SAddr(SAddr, Req, K) :-

lookup@NAddr(NAddr, Req, K),

node@NAddr(NAddr, N),

succ@NAddr(NAddr, Succ, SAddr),

K not in (N, Succ].

Implementation: From OverLog to Dataflow

- Traditional problem in databases
- Turn logic into relational algebra
  - Joins, projections, selections, aggregations, etc.

From OverLog to Dataflow

```
response@R(R, K, SI) : - lookup@NI(NI, R, K),
    node@NI(NI, N), succ@NI(NI, S, SI), K in (N, S].
lookup@SI(SI, R, K) :- lookup@NI(NI, R, K),
    node@NI(NI, N), succ@NI(NI, S, SI), K not in (N, S].
```

lookup →

From OverLog to Dataflow

R1 response@R(R, K, SI) : - **lookup@NI(NI, R, K),**
node@NI(NI, N), succ@NI(NI, S, SI), K in (N, S].

R2 lookup@SI(SI, R, K) :- lookup@NI(NI, R, K),
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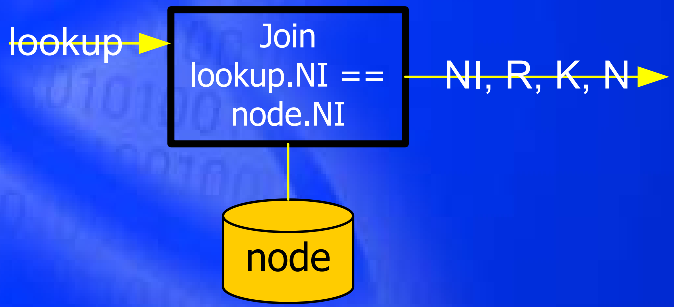

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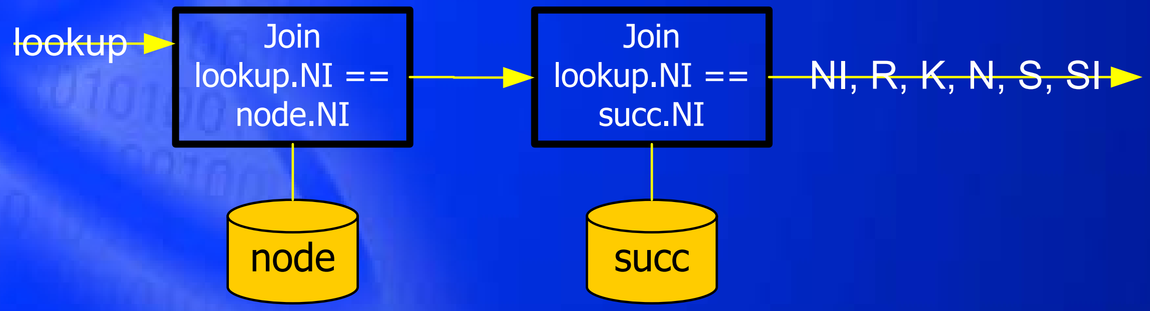

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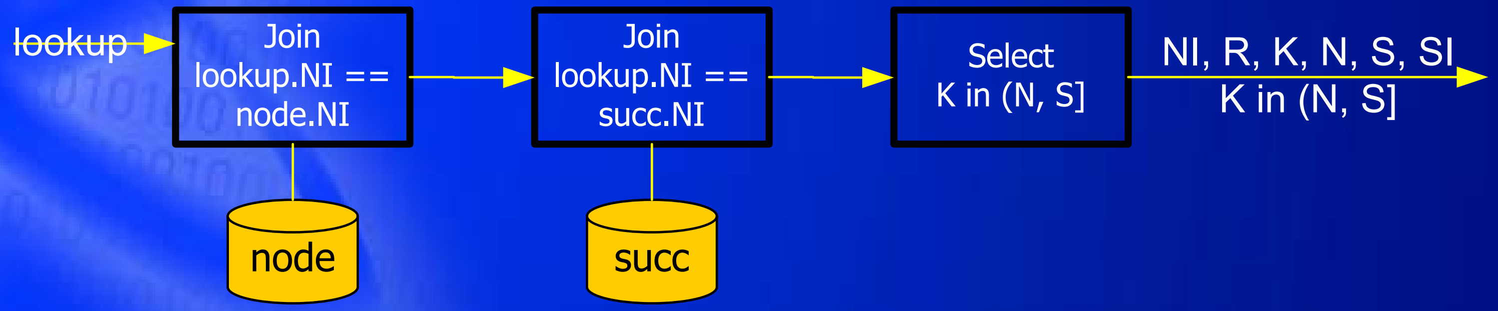

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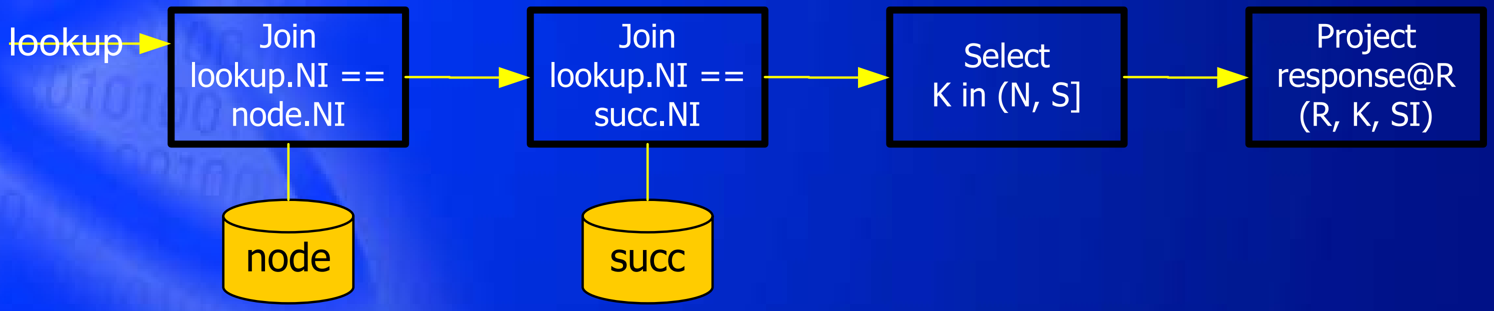

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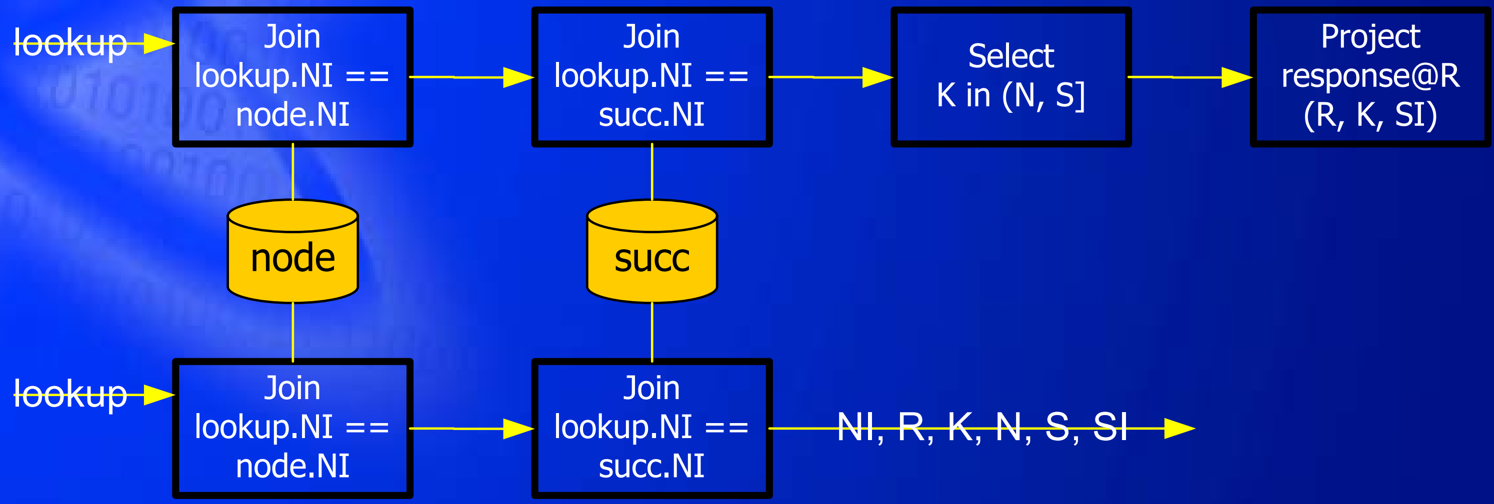

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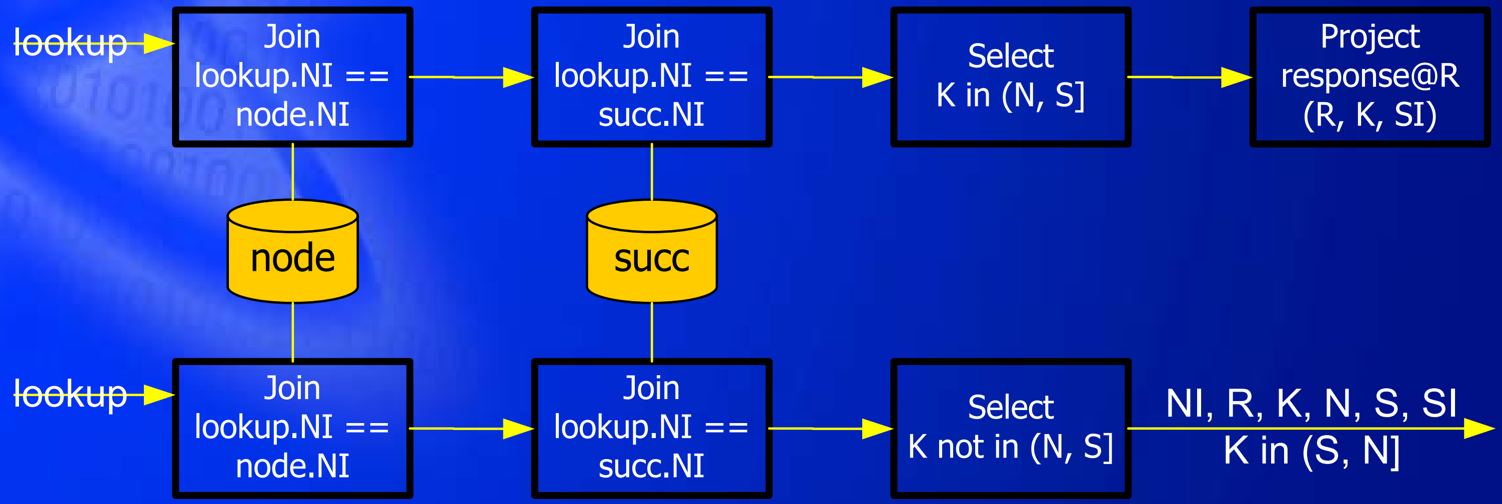

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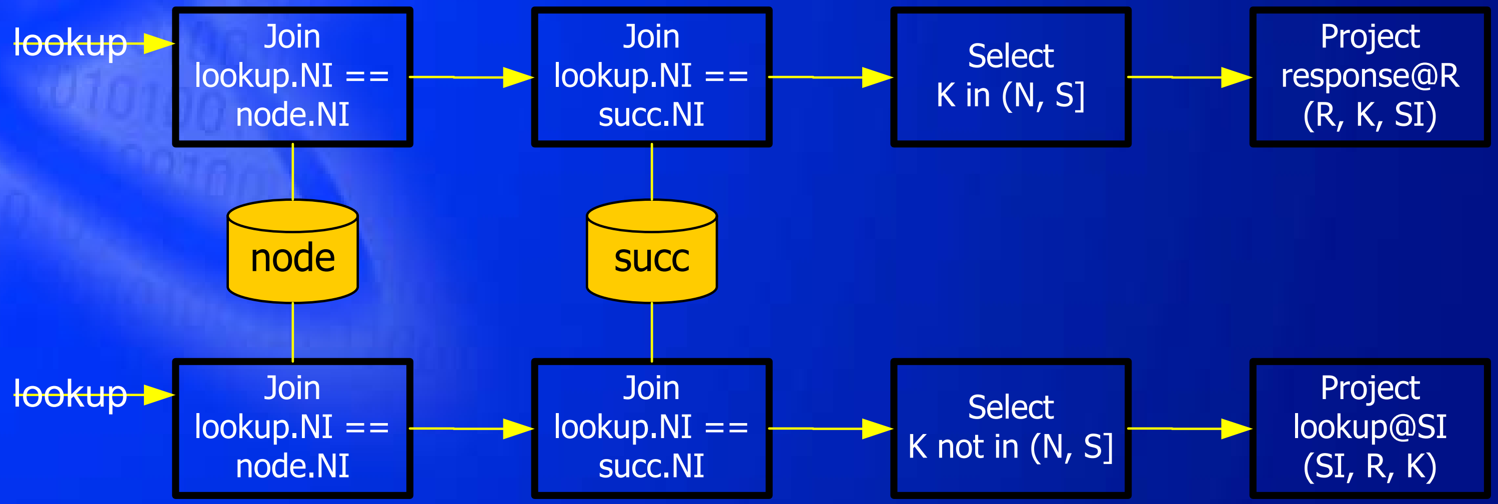
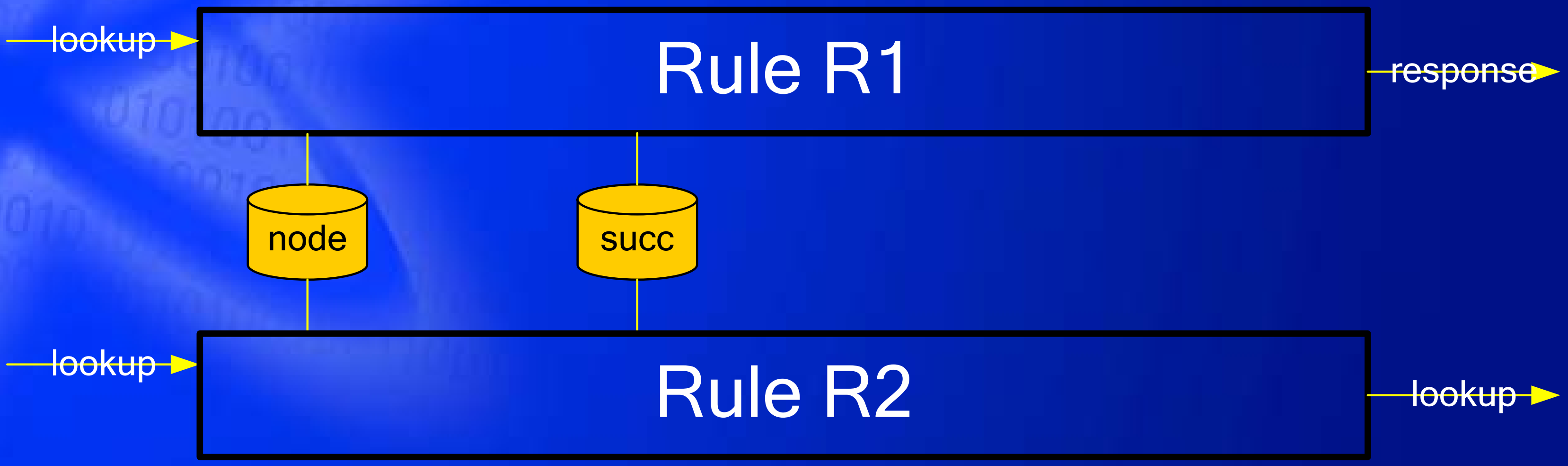
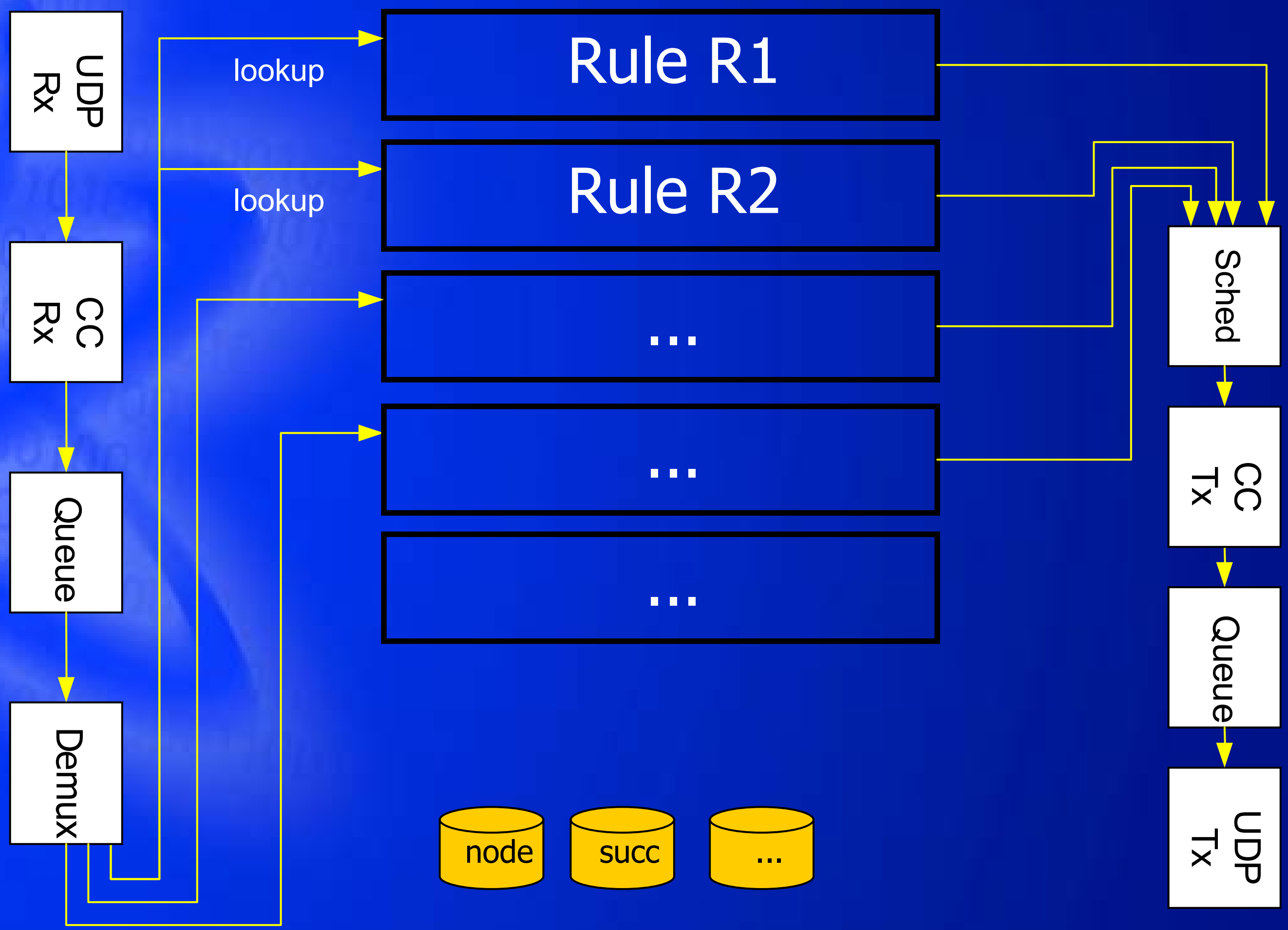


From OverLog to Dataflow

- One *rule strand* per OverLog rule
- Rule order is immaterial
- Rule strands could execute in parallel

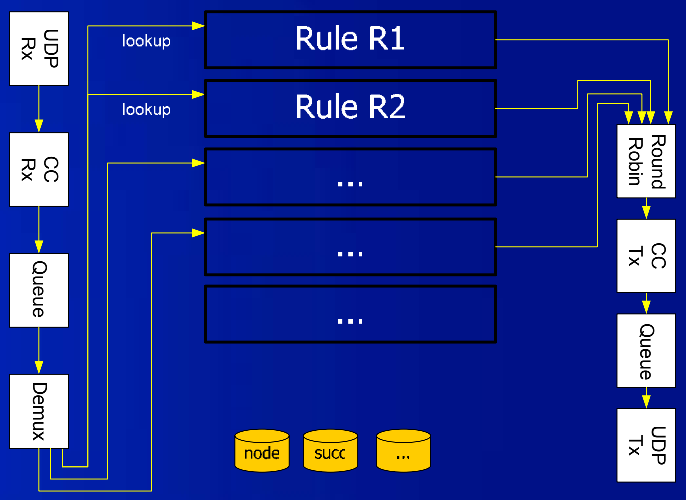


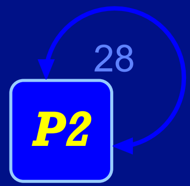
From OverLog to Dataflow



Implementation

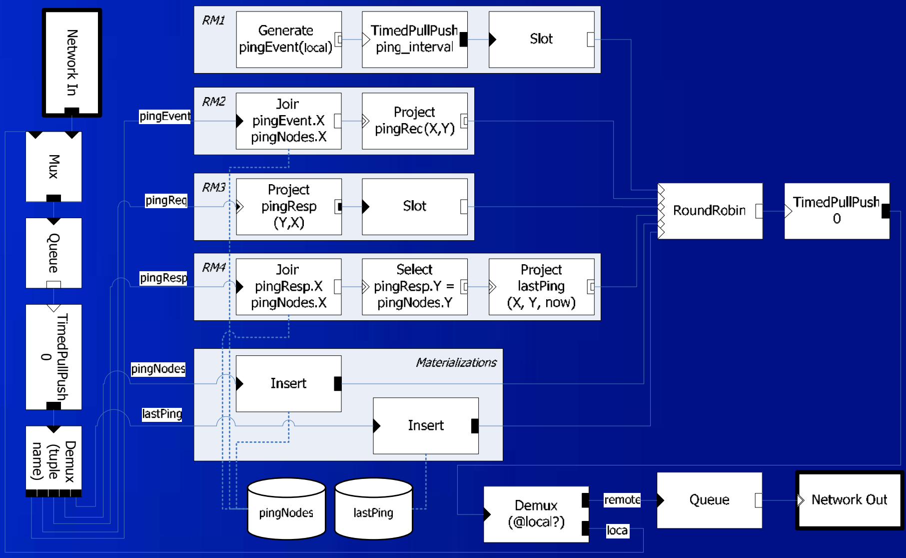
- Elements are C++ objects
  - Reference-counted immutable tuples
- Fast tuple hand-off
  - ~50 ia32 instructions, ~300 cycles
- Currently single-threaded
  - Select loop, timers, etc.
- Element state stored in tables
  - C.f. database catalogues: reuse data model wherever appropriate
- Conventional Bison/Flex parser





It actually works.

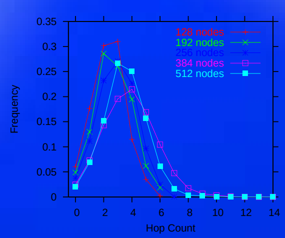
- For instance, we implemented Chord in P2
  - Popular distributed hash table
  - Complex overlay
  - Dynamic maintenance

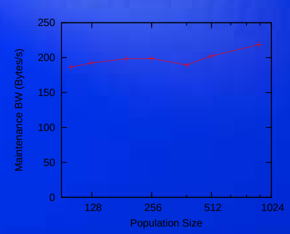


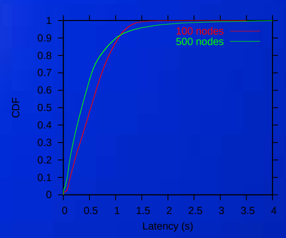
- How do we know it works?
  - Same high-level properties
    - Logarithmic overlay diameter
    - Logarithmic state size
    - Consistent routing with churn
  - Comparable performance to hand-coded implementations

Key point: remarkably concise overlay specification

- Full specification of Chord overlay, including
  - Failure recovery
  - Multiple successors
  - Stabilization
  - Optimized maintenance
- 44 OverLog rules
- And it runs!







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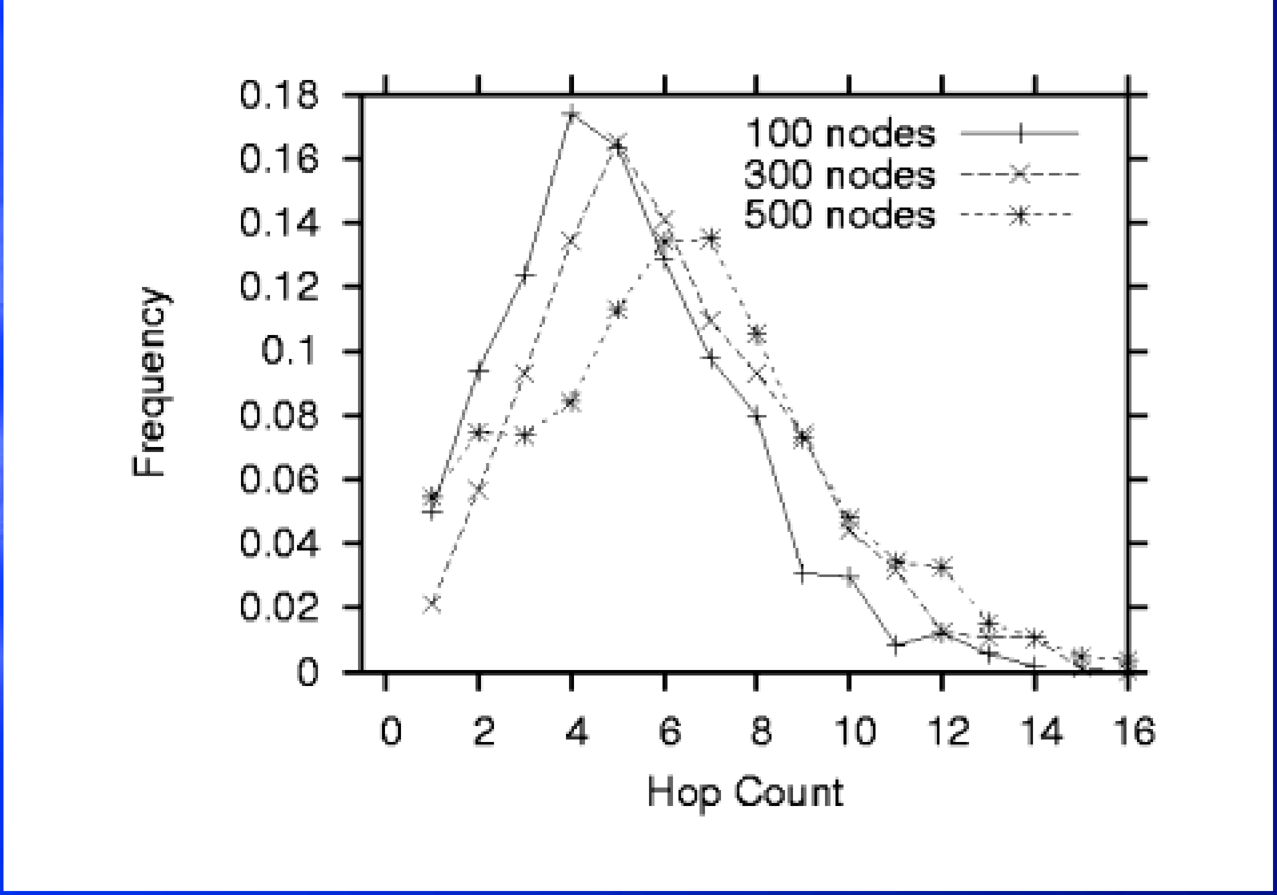
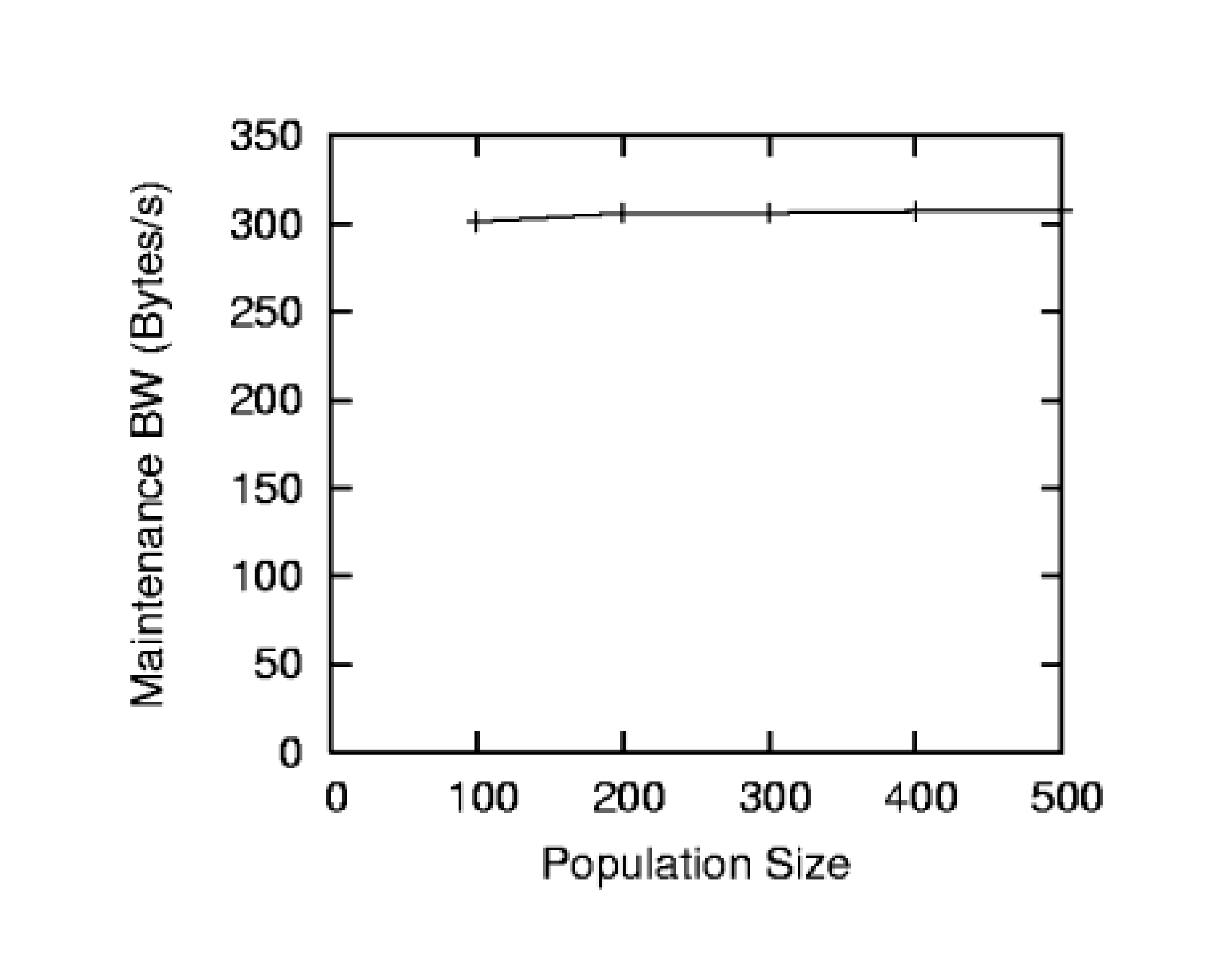
Comparison: MIT Chord in C++

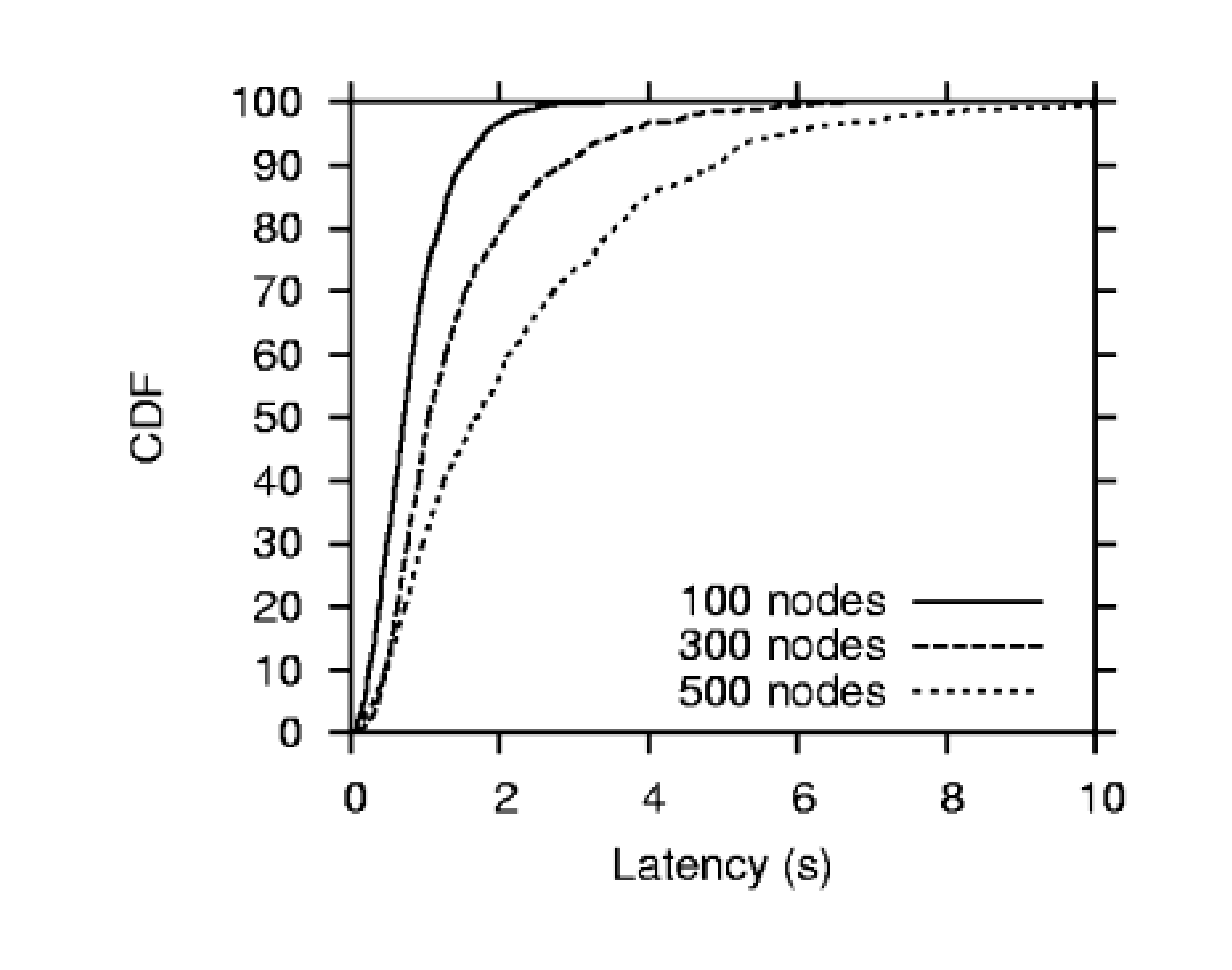
Lookup length in hops



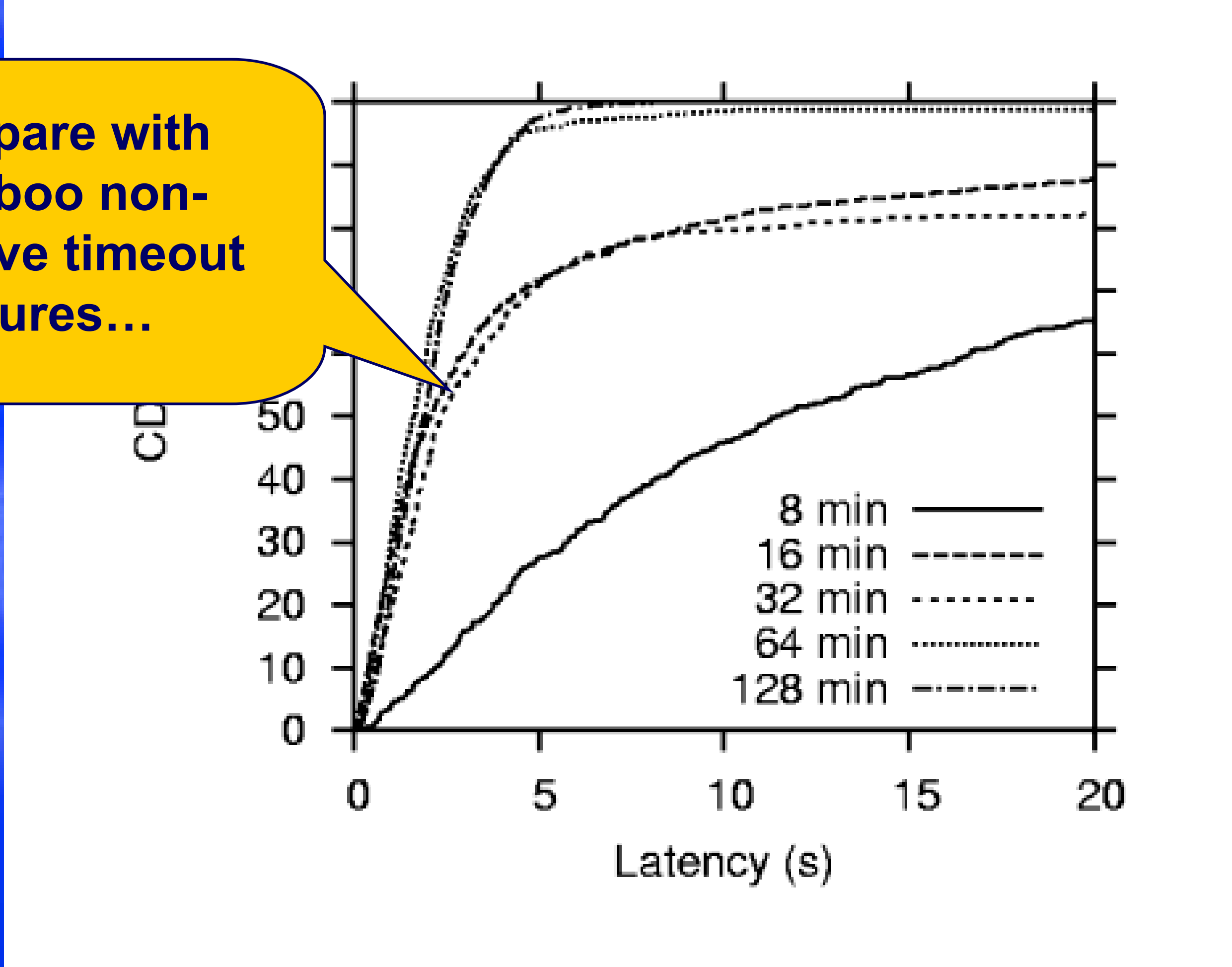
Maintenance bandwidth
(comparable with MIT Chord)



Latency without churn

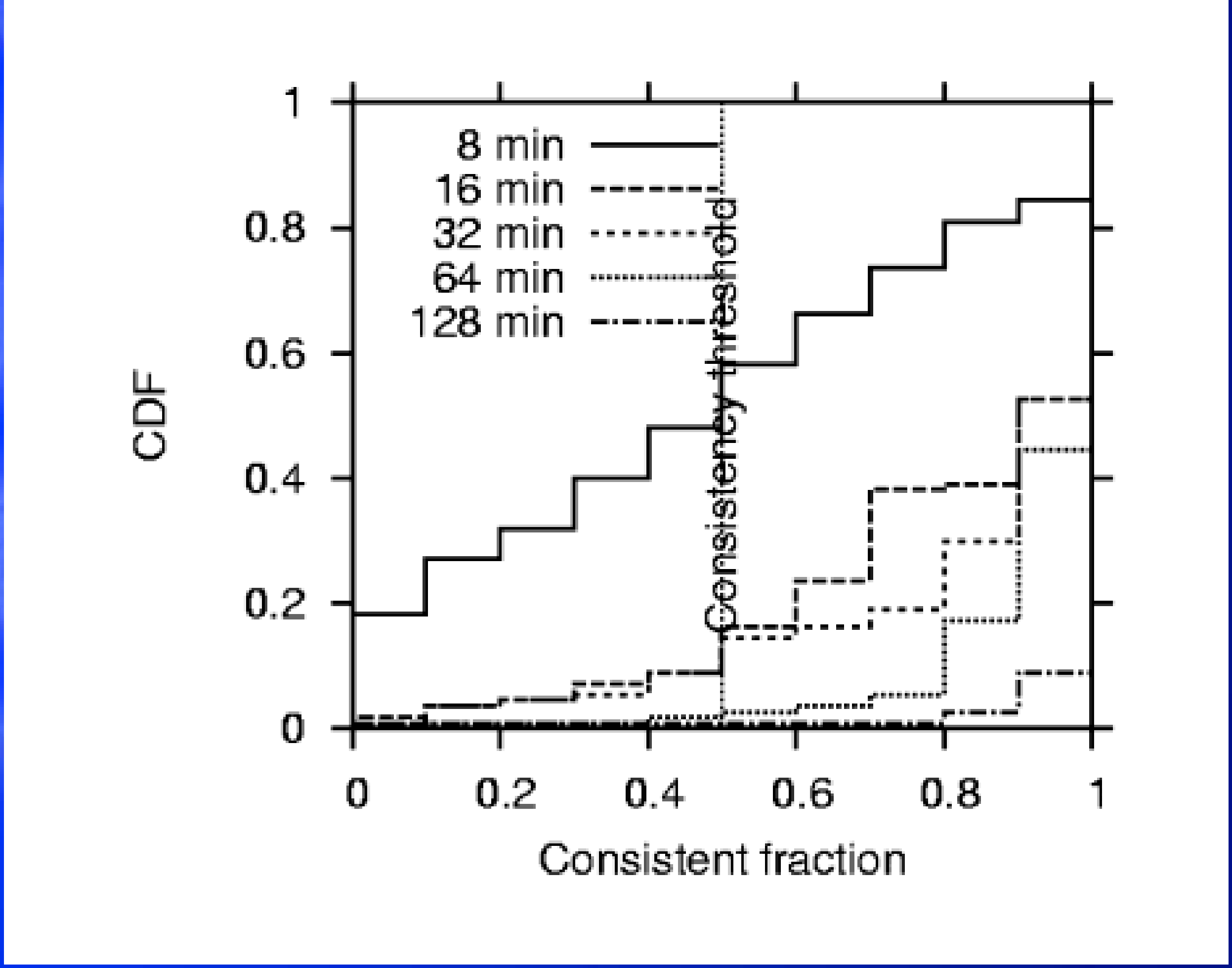


Latency under churn



Compare with Bamboo non-adaptive timeout figures…

Consistency under churn



The story so far:

- Can specify overlays as continuous queries in a logic language
- Compile to a graph of dataflow elements
- Efficiently execute graph to perform routing and forwarding
- Overlays exhibit similar performance characteristics

But …

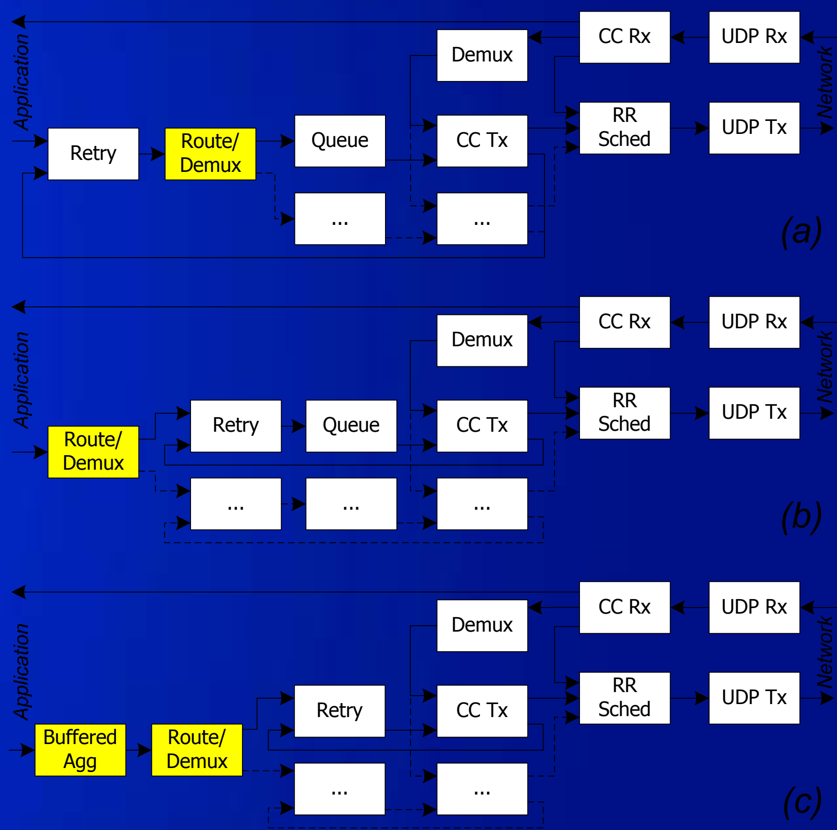
Once you have a distributed query processor, lots of things fall off the back of the truck…

What else does this buy you? Introspection (w/ Atul Singh, Rice)

- Overlay invariant monitoring: *a distributed watchpoint*
  - "What's the average path length?"
  - "Is routing consistent?"
- Execution tracing at "pseudo-code" granularity: *logical stepping*
  - Why did rule R7 trigger?
- … and at dataflow granularity: *intermediate representation stepping*
  - Why did that tuple expire?
- Great way to do distributed debugging and logging
  - In fact, we use it and have found a number of bugs…

What else does this buy you? 2. Transport reconfiguration

- Dataflow paradigm thins out layer boundaries
  - Mix and match transport facilities (retries, congestion control, rate limitation, buffering)
  - Spread bits of transport through the application to suit application requirements
  - *Automatically!*



In fact, a rich seam for future research...

- Reconfigurable transport protocols
- Debugging and logging support
- The "right" language – global invariants
  - Use distributed joins as abstraction mechanism
- Optimization techniques
  - Inc. multiquery optimization
- Monitoring other distributed systems and networks
  - Evolve towards more general query processor?
  - PIER heritage returns

Summary

- Overlays enable distributed system innovation
- We'd better make them easier to build, reuse, understand
- P2 enables
  - High-level overlay specification in OverLog
  - Automatic translation of specification into dataflow graph
  - Execution of dataflow graph
- Explore and Embrace the trade-off between fine-tuning and ease of development
- Get the full immersion treatment in our paper in SOSP '05, code release imminent

Thanks! Questions?

- A few to get you started:
  - Who cares about overlays?
  - Logic? You mean Prolog? Eeew!
  - This language is really ugly. Discuss.
  - But what about security?
  - Is anyone ever going to use this?
  - Is this as revolutionary and inspired as it looks?