Implementing Declarative Overlays

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Broad Challenge: Network Routing Implementation

- Protocol-centric approach is usual:
  - Finite state automata
  - Asynchronous messages / events
  - Intuitive, but:

- Hard to:
  - reason about structure
  - check/debug
  - compose/abstract/reuse

- But few, if any, new abstractions have emerged for the problem.
Talk Overview

• Approach: take high-level view
  - Routing and Query Processing
  - Declarative specifications
• P2: a declarative overlay engine
  - OverLog language
  - Software dataflow implementation
• Evaluation: Chord as a test case
• Ongoing and future work
Declarative Networking

• 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 and 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.
Distributed Continuous Query Processing

• Relatively new and active field
  - SDIMS, Mercury, IrisLog, Sophia, etc., in particular PIER
  - ⇒ May not have all the answers yet

• But brings a wealth of experience and knowledge from database systems
  - Relational, deductive, stream processing, etc.
Goal: Declarative Networks

1. Express network properties as queries in a high-level declarative language
   - More than configuration or policy language
   - Apply static checking
   - Modular decomposition

2. Compile/interpret to maintain network
   - Dynamic optimization (e.g. eddies)
   - Sharing of computation/communication
Other advantages

• Can incorporate other knowledge into routing policies
  – E.g., physical network knowledge
• Naturally integrates discovery
  – Often missing from current protocols
• Also provides an abstraction point for such information
  – Knowledge itself doesn’t need to be exposed.
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
Specific case: overlays

- **Application level:**
  - e.g. DHTs, P2P networks, ESM, etc.

- **IP-oriented:**
  - e.g. RON, IPVPNs, SOS, M/cast, etc.

- **More generally:** routing fn of any large distributed system
  - e.g MS Exchange, mgmt systems
Why overlays?

• **Overlays in a very *broad* sense**
  - Any application-level routing system
  - Email servers, multicast, CDNs, DHTs, etc.
  - ⇒ broad applicability

• **Ideal test case**
  - Clearly deployable short-term
  - Defers interoperability issues
  - Testbed for other domains

• **The overlay design space is wide**
  - ⇒ ensure we cover the bases
Background

- **PIER**: distributed relational query processor (Huebsch et.al.)
  - Used DHT for hashing, trees, etc.
- **Click**: modular s/w forwarding engine (Kohler et.al.)
  - Used dataflow element graph
- **XORP router** (Handley et.al.)
  - Dataflow approach to BGP, OSPF, etc.
P2: A declarative overlay engine

OverLog specification

Parser → Planner

Received Packets

Software Dataflow Graph

Sent Packets
Data Model

- Relational tuples
- Two types of named relation:
  - Soft-state tables
  - Streams of transient tuples
- Simple, natural model for network state
  - Concisely expressed in a declarative language
Language: DataLog

- Well-known relational query language from the literature
  - Particularly deductive databases
  - Prolog with no imperative constructs
  - Equivalent to SQL with recursion

- OverLog: variant of DataLog
  - Streams & tables
  - Location specifiers for tuples
Why DataLog?

- **Advantages:**
  - Generality allows great flexibility
  - Easy to map prior optimization work
  - Simple syntax, easy to extend
- **Disadvantages:**
  - Hard for imperative programmers
  - Structure may not map to network concepts
- **Good initial experimental vehicle**
Overlog by example

- **Gossiping a mesh:**
  - materialise(neighbour, 1, 60, infinity).
  - materialise(member, 1, 60, infinity).

  - gossipEvent(X) :- localNode(X), periodic(X,E,10).

  - gossipPartner@X(X,Y) :- gossipEvent@X(X), neighbour@X(Y).

  - member@Y(Z) :- gossipPartner@X(X,Y), coinflip(weight), member@X(Z).
Software Dataflow Graph

• Elements represented as C++ objects
• V. efficient tuple handoff
  – Virtual fn call + refcounts
• Blocking/unblocking w/ continuations
• Single-threaded async i/o scheduler
Typical dataflow elements

• Relational operators
  - Select, join, aggregate, groupby
  - Generalised projection (PEL)

• Networking stack
  - Congestion control, routing, SAR, etc.

• “Glue” elements
  - Queues, muxers, schedulers, etc.

• Debugging
  - Loggers, watchpoints, etc.
Evaluation: Chord test case

• Why Chord?
  - Quite complex overlay
  - Several different data structures
  - Maintenance dynamics, inc. churn

• Need to show:
  - We can concisely express Chord’s properties
  - We can execute the specification with acceptable performance
Chord (Stoica et. al. 2001) a “distributed hash table”

- Flat, cyclic *key space* of 160-bit identifiers
- Nodes pick a random identifier
  - E.g. SHA-1 of IP address, port
- *Owner* of key k: node with lowest ID greater than k
- Efficiently route to owner of any key in \(\sim \log(n)\) hops
Chord data structures

- **Predecessor node**
- **Successor set**
  - log(n) next nodes
- **Finger table**
  - Pointers to power-of-2 positions around the ring
Chord dynamics

- Nodes *join* by looking up the owner of their ID
- Download successor sets from neighbours and perform lookups for fingers
- Periodically measure connectivity to successors & fingers
- *Stabilization* continuously optimizes finger table
Example: Chord in 33 rules
Dataflow graph
(some of it, at least)
Comparison: MIT Chord in C++
Perhaps a fairer comparison...

- **Macedon** *(OSDI 2004)*
  - State machines, timers, marshaling, embedded C++
- **Macedon Chord**: 360 lines
  - 32-bit IDs, no stabilization, single successor
- **P2 Chord**: 34 lines
  - 160-bit IDs, full stabilization, log(n) successor sets, optimized
Performance?

- Note: aim is acceptable performance, not necessarily that of hand-coded Chord

- Analogy: SQL / RDBM systems
Maintenance bandwidth
(comparable with MIT Chord)
Latency without churn

CDF

Latency (s)

100 nodes — red line
500 nodes — green line
Latency under churn

CDF

Latency (s)

8 min
16 min
32 min
64 min
Ongoing work

• More overlays!
  - Pastry, parameterized small-world graphs
  - Link-state, distance vector algorithms
  - Assorted multicast graphs
• Proper library interface
  - Code release later this summer
• Integrate discovery
  - Exploit power of full query processor
  - Can implement PIER in P2
  - Integrated management, monitoring, measurement
Ongoing work

• Rich seam for further research!
  - The “right” language (SIGMOD possibly)
  - Optimization techniques
  - Proving safety properties
• Reconfigurable transport protocols
  - Dataflow framework facilitates composition
  - P2P networks introduce new space for transport protocols
• Debugging support
  - Use query processor for online distributed debugging
  - Potentially very powerful
Conclusion

• Diverse overlay networks can be expressed concisely in a OverLog
• Specifications can be directly executed by P2 to maintain the overlay
• Performance of P2 overlays remains comparable with hand-coded protocols
Long-term implications

• An abstraction and infrastructure for radically rethinking networking
  - One possibility: System R for networks

• Where does the network end and the application begin?
  - E.g. can run queries to monitor the network at the endpoints
  - Integrate resource discovery, management, routing
  - Chance to reshuffle the networking deck
Thanks! Questions?

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It's real...
Consistency under churn

CDF

Consistency threshold

8 min
16 min
32 min
64 min

Consistent fraction

Consistency under churn

CDF

Consistency threshold

8 min
16 min
32 min
64 min

Consistent fraction
Bandwidth usage under churn

![Graph showing bandwidth usage over session time](attachment:image.png)
P2: A declarative overlay engine

- Everything is a declarative query
  - Overlay construction, maintenance, routing, monitoring
- Queries compiled to software dataflow graph and directly executed
- System written from scratch (C++)
  - Deployable (PlanetLab, Emulab)
  - Reasonable performance so far for deployed overlays