Big idea here: declarative languages have much broader applicability than previously realized!

- Gray’s Turing Lecture: Automatic Programming as a Grand Challenge
- Lampson’s response in JACM 50'th anniversary
- Can the "brittle" declarative languages of data management extend elsewhere?
- Declarative Domain-Specific Languages
  - How many domains must we knock off before we decide it’s no longer a DSL?
  - Overlay Nets, Sensornets Distributed Systems, Compilers, ML, Robotics, Security ...

- The SOSP 2005 paper on P2
  - The first shot at making declarative networking real
  - We had earlier done Declarative Routing using PIER, our p2p query engine, but programs were basically just illustrations of a concept
- Set ourselves the challenge to do complex overlays, not just toy examples: Chord!

- Click meets Datalog
- Much work since then
  - Clean up semantic messes: bottom-up design of a declarative system had pros/cons.
  - Realize the promise: automatically optimize, prove properties, show more stuff we can easily do

Background: Datalog

- Post-dates Prolog. An attempt to do 2 things to Prolog:
  - remove all operational semantics
  - allow for batch-oriented (dataflow) processing, a la database engines
  - basic SQL plus recursively defined views
- Basics:
  - Relational structures
  - Extensional Data Base (EDB): stored "facts". Think of tables in SQL. Expressed via "facts".
    - parent("George HW", "George W").
  - Intensional Data Base (IDB): derived facts (deduction). Think of "views" in SQL. Strictly logical entities -- keep lazy evaluation in mind, it will keep you from getting confused.
    - scalars: variables (capital letters), constants
    - atoms: p(a1, ..., an) where p (lowercase letters) is a relation(predicate) name, a1...an are variables or constants
    - rules: "head" and "body"
      - ancestor(X, Y) :- parent(X,Y).
      - ancestor(X, Y) :- ancestor(X, Z), parent(Z, Y).
- Things to keep in mind
  - all uses of a predicate have same arity
  - multiple appearances of predicate in head = disjunction (UNION)
  - body predicates implicitly involved in conjunction (AND)
  - unification across body predicates of a rule via variable-matching (equi-join)
  - reordering rules in a program does not change meaning
  - reordering predicates in a body does not change meaning
- Now, the syntax is mathematical logic, meaning that it’s just a grammar defining legal sentences. We need a "model" to define what we mean by this grammar.
  - want model to be consistent with existence/non-existence of facts
  - what is a good model?
    - Minimal models are good (can’t remove any fact and stay consistent)
    - Unique Minimal Model would be nice!
  - simple semantics that "work" (i.e. provide a unique minimal model):
    - an atom is true for "bindings" of its variables iff the arguments form a tuple of the relation
    - whenever a binding of values to each variable makes all subgoals in the body true, the rule asserts that the head is also true
    - Nice: clean, intuitive declarative semantics that has attractive logical properties
- Even better: this model arises naturally from a simple dataflow implementation!
  - a.k.a. "forward chaining" or "bottom up" (as opposed to Prolog’s "backward chaining" or "top down")
  - and the implementation is amenable to much optimization. (yay!)
- Semi-Naive Evaluation
  - basic idea is to keep "joining in" newly derived tuples against previously derived tuples until you hit a "fixpoint".
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- **Background: Datalog**
  - Even better: this model arises naturally from a simple dataflow implementation!

- **Semi-Naive Evaluation**
  - The basic idea is to keep “joining in” newly derived tuples against previously derived tuples until you hit a “fixpoint”.
  - Visualize descending the tree in “levels”: find children of root. Then grandchildren. Then great-grandchildren. (In a cyclic relation, remove duplicates as you go.)
  - Isn’t the ancestor example dorky?
    - But look:
      - `path(X, Y) :- link(X, Y).`
      - `path(X, Y) :- path(X, Z), link(Z, Y).`
    - Or even better:
      - `path(X, Y, Y, Cost) :- link(X, Y, Cost).`
      - `path(X, Y, Z, C1+C2) :- path(X, Z, NextHop, C1), link(Z, Y, C2).`
  - Now add this:
    - `minCost(X, Y, min<C>) :- path(X, Y, NextHop, C).`
    - `bestPath(X, Y, NextHop, Cost) :- path(X, Y, NextHop, Cost), minCost(X, Y, Cost).`
    - Hey, that’s shortest-path routing -- a network protocol! (sort of. still centralized)

- **A side note: aggregation, negation & stratified versions**
  - The "min" above complicates our semantics
  - so does NOT p() -- i.e. negation (same as count<!> = 0
  - "non-monotonic": i.e. the answer (or its subsequent use) may not grow as we deduce more facts, recursively
  - the min is computed over what set exactly?
    - idea: identify the minimal model over path, and define minCost on that!
  - draw a **rule dependency graph**.
    - partition the graph into **strata**, such that each stratum contains no negation/aggregation edges internally
      - if the resulting graph of strata is acyclic, the program is **stratifiable**
    - stratified semantics define each stratum with respect to the (unique) minimal model of the preceding strata
    - i.e. compute fixpoints following the partial order on strata

- **So far we have seen...**
  - **Datalog**
    - With stratified negation/aggregation
    - It can represent an important networking task: routing on shortest paths
    - But in a centralized implementation. Kind of silly!
    - **How can we get a distributed version?**
  - **Datalog + Horizontal partitioning = Networking.**
    - partitioning a la classical parallel DBs, a.k.a. “Map”.
    - the trick: partition on a field of type “address” -- then “Map” is the declarative version of “Send”, says where data shall live.
      - `link(@X, Y).`
      - `path(@X, Y, Y, P, C) :- link(@X, Y, C), P = f_concatPath(link(X,Y,C), nil).`
      - `path(@X, Y, Z, P, C1+C2) :- link(@X, Z, C1), path(@Z, Y, N, P2, C2), P = f_concatPath(link(X,Z,C1),P2).`
    - localization
      - the recursive rule above has to do a distributed join
      - use a syntactic rewrite to describe that. replace the last rule with:
        - `link_d(X, @Z, C) :- link(@X, Z, C).`
        - `path_d(@X, Y, Z, P, C1+C2) :- link_d(X, @Z, C1), path_d(@Z, Y, N, P2, C2), P = f_concatPath(link(X,Z,C1),P2).`
      - OMG! That is Path Vector routing, a classic internet protocol used in BGP (among other places).
      - Wait, it gets better! Could have done join reordering on the recursive rule, and then localized.
        - `path_d(@X, Y, Z, C1+C2) :-path_d(@X, Z, P1, C1), link_d(@Z, Y, C2).`
      - rewrite to:
        - `path_d(@X, @Z, P1, C1) :- path_d(@X, Z, P1, C1).`
        - `path_d(@X, Y, Z, C1+C2) :- path_d(@X, @Z, P1, C1), link_d(@Z, Y, C2), P = f_concatPath(P1, link(Z,Y,C2)).`
      - This is the key to what’s called Dynamic Source Routing, which is widely used in wireless networking.
    - This is more than mere conciseness!
      - We have found an avenue to treat protocol design as a query optimization problem
        - Just say what routes you want, and pick the protocol to find them by understanding performance issues
        - Critical, because the world is getting more complicated than 2 classes of connections (wireless vs. Internet!)

- **Some Declarative Networking details we’re glossing over**
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- Time, state, network delays, and effects on semantics
  - Tricky! Much of this is confused in the early papers. Coming clearer recently.
- **Soft state**: a key persistence model in networking
  - data items have expiry as of some time after *arrival at the destination*
  - persistence is achieved through periodic sender retransmission
  - passive failure detection -- handles disconnection elegantly
  - soft-state IDB?
    - soft-state heads? head/body differ in their lifetimes?
    - events are soft-state with an "instantaneous" expiry!
- Time in P2: One local event per clock "tick"
  - clock events from *periodic* an infinite clock eventstream
  - network arrival events
  - take the current tick's single event as a one-fact table
  - expire stale soft state
  - treat the result as EDB, run datalog to (local) fixpoint
  - expire the event
  - How about distributed time?!
- How do we detect distributed fixpoint? Esp for strata?
  - Can make this crisp via consensus (Paxos), but may not want to.

- **Why does Datalog fit so well for so many things?**
  - networks are graphs, want recursive queries on graphs
    - routing example above
  - (repeated) asynchronous communication is basically join: match pending requests to stream of responses
    - pending_request(@X, Y, Args) :- request(@X, Y, Args).
    - request(X, @Y, Args) :- request(@X, Y, Args).
    - response(@X, Y, Result) :- request(X, @Y, Args), Result = f_doit(@Y, Args).
  - forward chaining is essentially dynamic programming
    - and D.P. optimizations can be simply expressed in datalog with stratified aggregation
    - note that D.P. is used lots of places including database query optimization, various machine learning algorithms, etc.
  - Note that monotonic Datalog can express PTime computations
    - Do you really want to do more than that over a network?!

- **Datalog variants exploding in the last 5 years!**
  - Declarative networking@Berkeley/Intel/Texas/Rice/etc.
  - Overlays, sensornet protocols
  - Distributed systems protocols (Paxos, Chandy-Lamport Snapshots, various forms of replication)
  - Machine Learning algorithms (JHU, Berkeley)
    - Inference (Junction trees, loopy BP) & Distributed Inference
    - Natural Language Processing (Dyna@JHU)
  - Compiler Analysis@Stanford
    - again, recursive queries, this time on call graphs
      - bddbddb
  - Security/Access protocols
    - Stanford, MSR
  - Modular Robotics
    - Meld@CMU
  - Datalog metacompilation@Berkeley
    - Evita Raced
      - e.g., simple datalog programs to build a dependency graph and check for stratification
      - e.g. Selinger-style dynamic programming
      - e.g. magic sets
  - OK, is this a set of DSLs?
• Well, they’re mostly yucky for traditional programmers
• Not unified
• How much of this is a syntax problem? how much is about domain specific optimizations?
  • Does metacompilation help with the latter?