Static Analysis of Active XML Systems

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Broader context:
Verification of data-driven systems

- growing area at the intersection of

  Databases and Computer-Aided Verification
- some promising theory and implementation
- potential for significant practical impact

Applications centered around a database

- Data-driven Web services
- E-commerce
- E-government
- Business process support
- Scientific applications

Complex, prone to costly bugs:

need for verification!

How to verify

General-purpose software verification techniques

- model checking

  usually requires finite-state abstraction

- theorem proving

  incomplete, requires expert user feedback

Unsatisfactory!

- Recent work: can do better by taking advantage of a proliferation of high-level specification tools

  WebML, Wave, Hilda: Web sites/services

  Siena (IBM): Business processes/artifacts

  Active XML (INRIA): XML services

- Ideal targets for verification

Good news: Can automatically verify significant classes of applications!

Active XML:
XML with embedded service calls

- integrates the XML and Web service paradigms
- controlled materialization of data

    keep dynamic data fresh

- implement evolving documents

Ongoing project in Serge's group

SIGMOD 2003, PODS 04/08/09, VLDB Journal,TODS

AXML for evolving documents

- Role of AXML service: support processing tasks

  loan applications, mail orders, tax forms, etc

- Evolution of a document reflects stages in carrying out the task
- Tasks are initiated by functions calls

  embedded function calls → sub-tasks

- Governed by workflow specified implicitly

  by constraints on document evolution

Outline

- Specific variant of AXML

  Guarded AXML (GAXML)

- Language for specifying temporal properties

  Tree-LTL

- Results: boundary of decidability of verification

Challenge: infinite-state system!

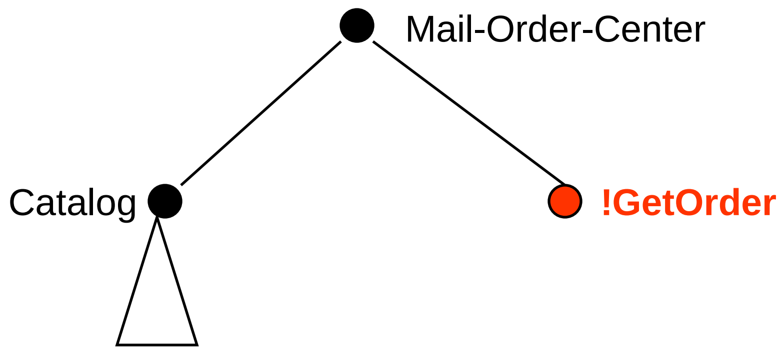
Guarded AXML

- guards used to control when a function is called and when the result is returned

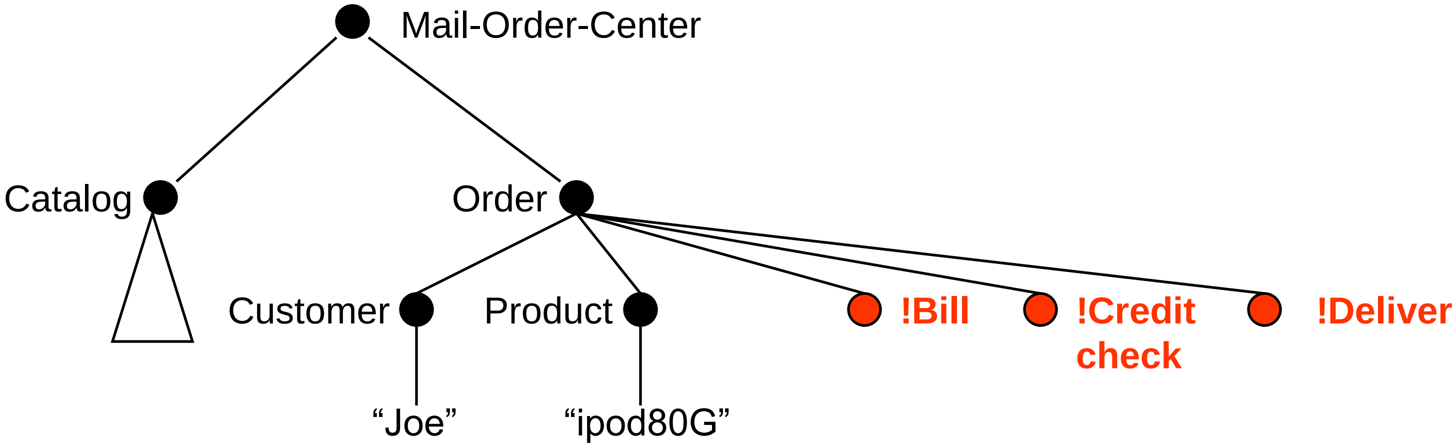
  powerful control mechanism

- data is passed as arguments to calls and as results of calls: defined by queries

GAXML by example



GAXML by example



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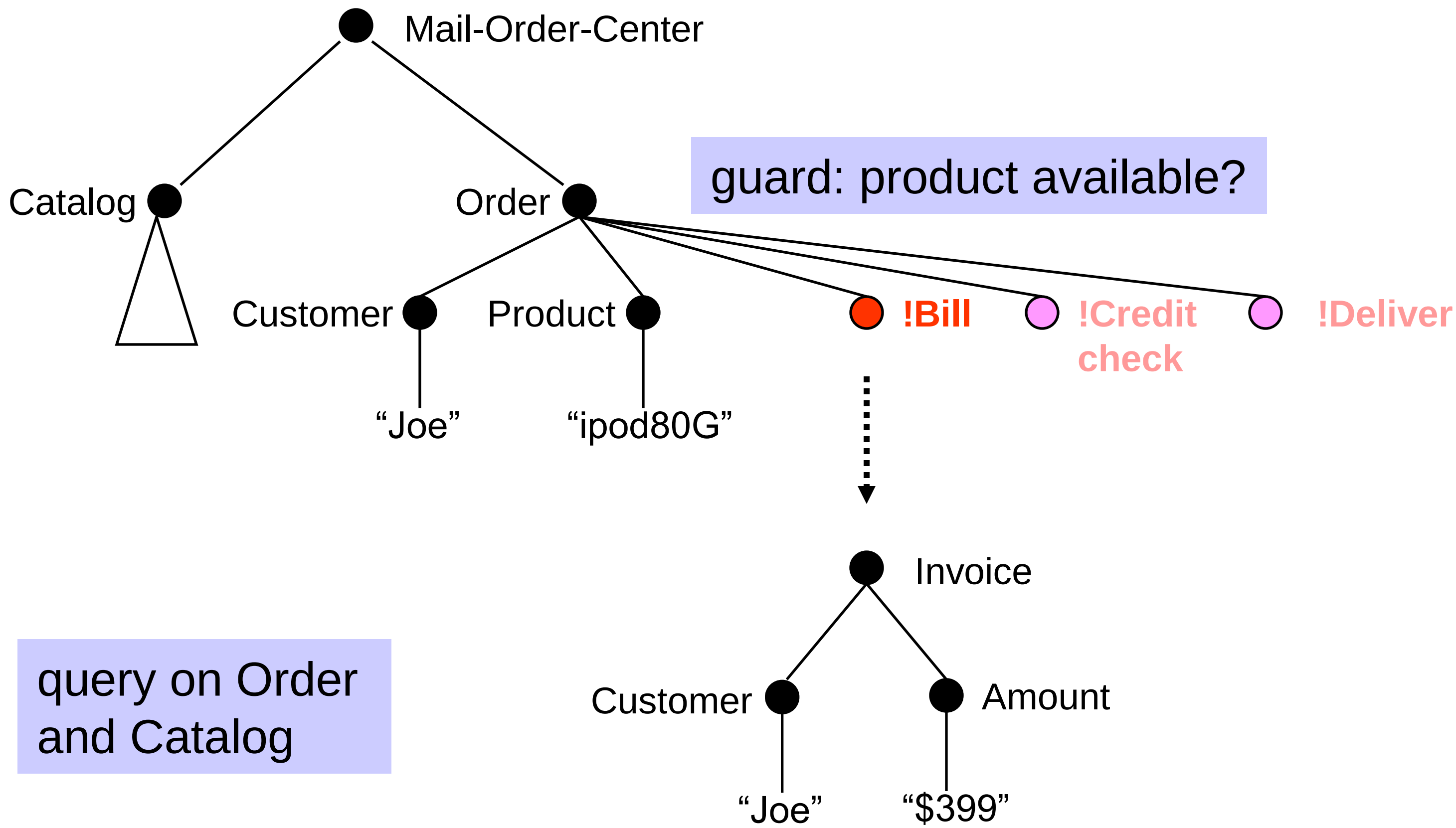

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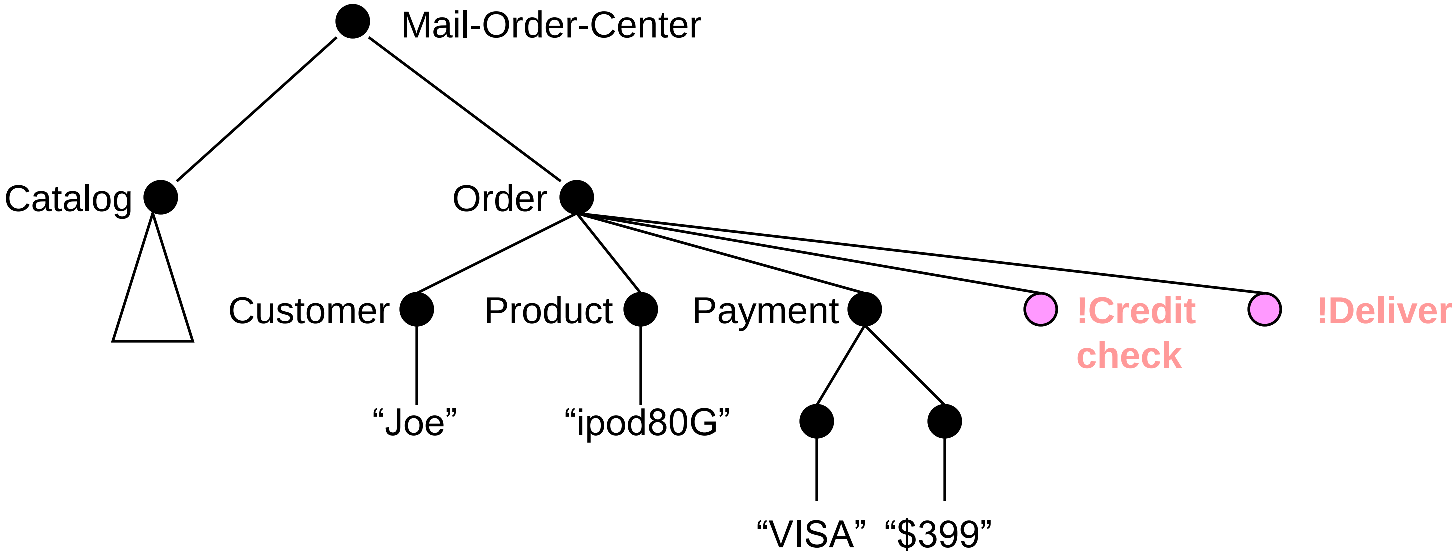

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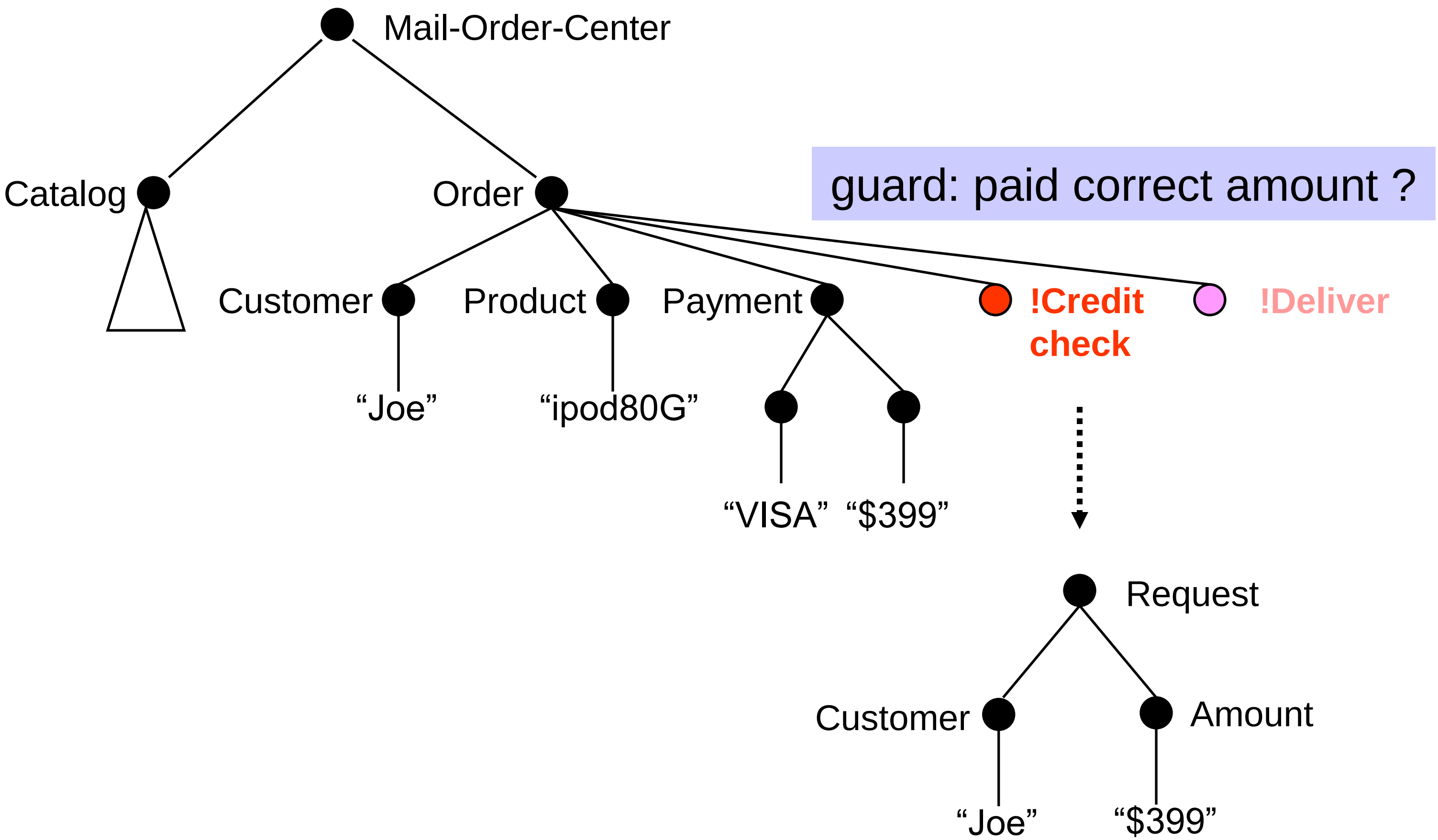

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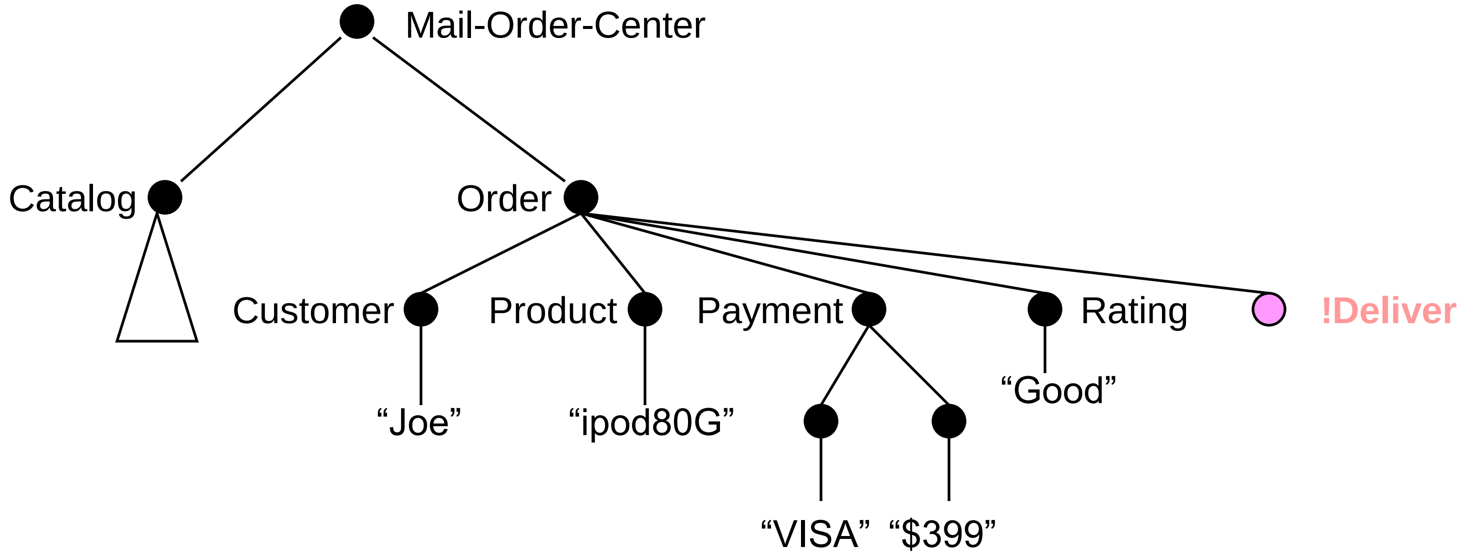

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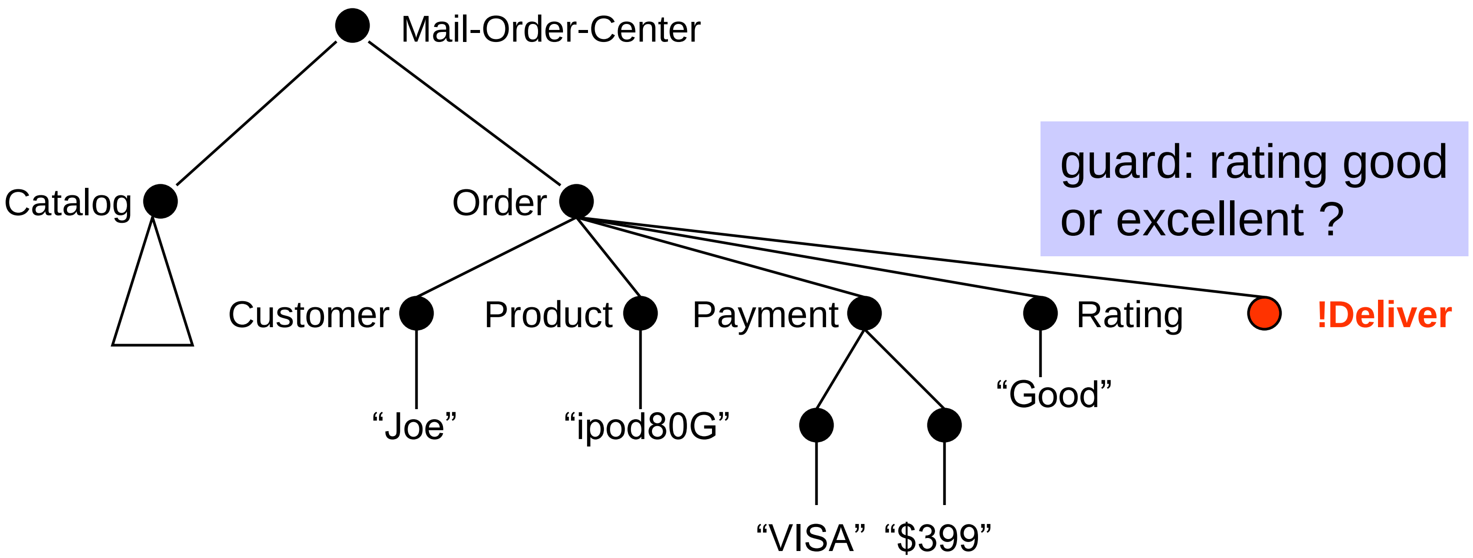

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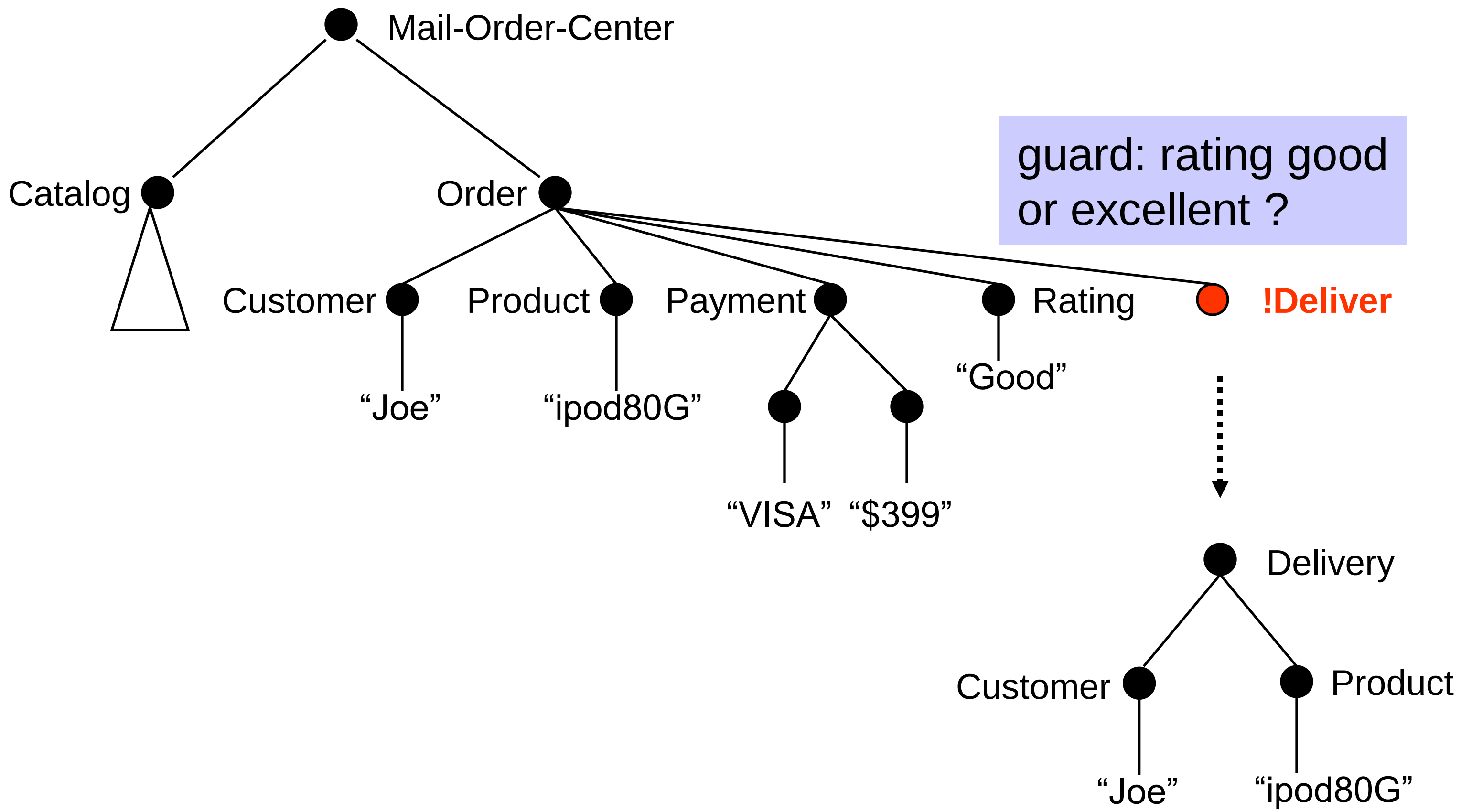

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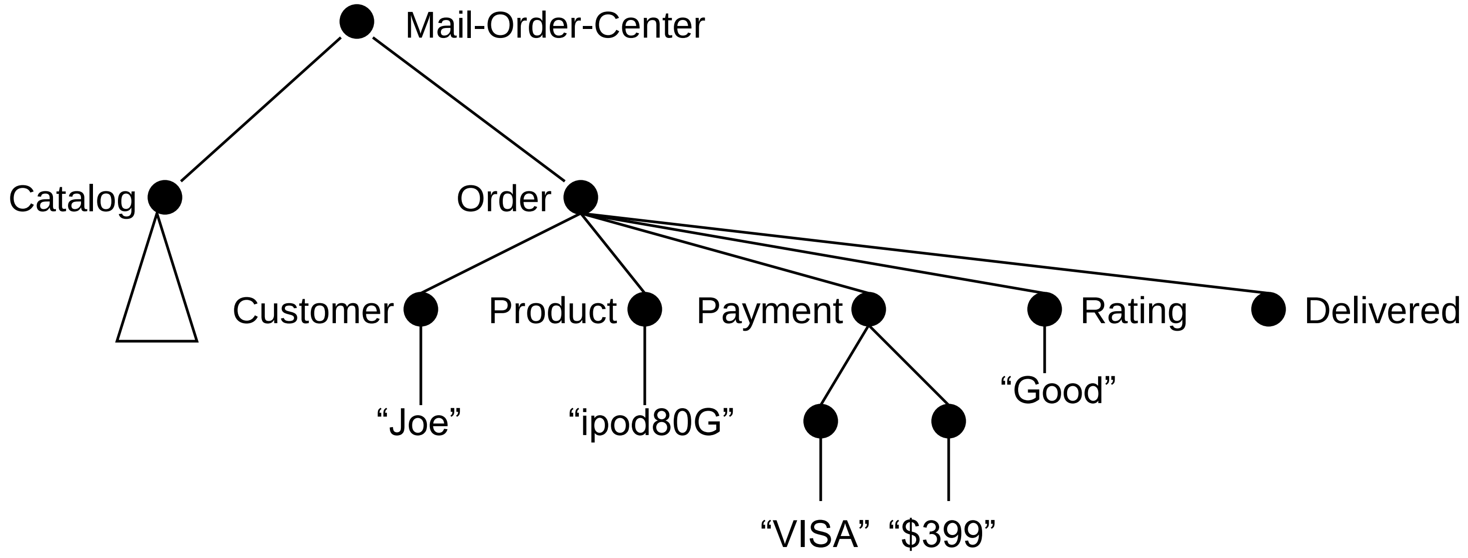

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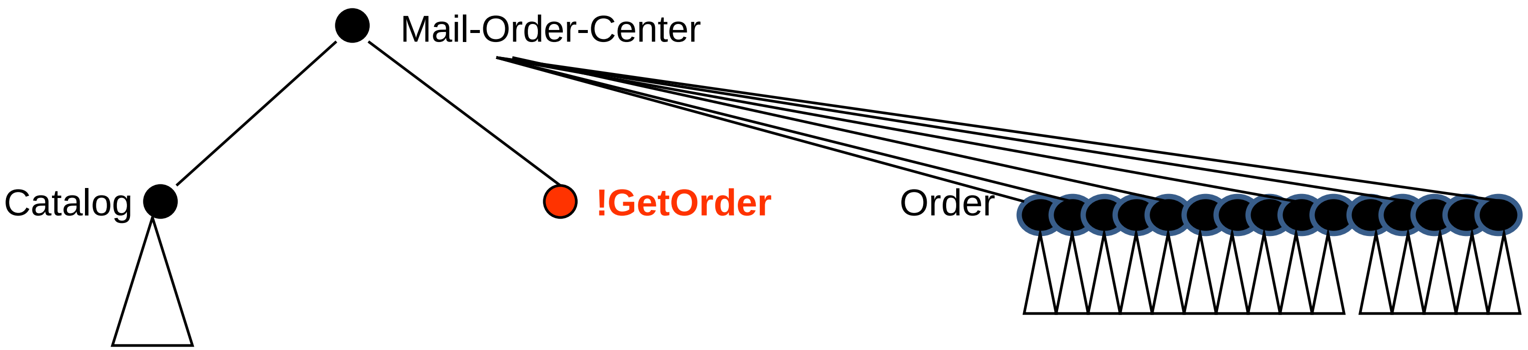


More details

- GAXML documents: unordered trees
- Internal nodes are labeled by tags
- Leaves are labeled by tags, data values, or function symbols

  !f   call to f

  ?f   running call to f

Static constraints on documents

- DTDs

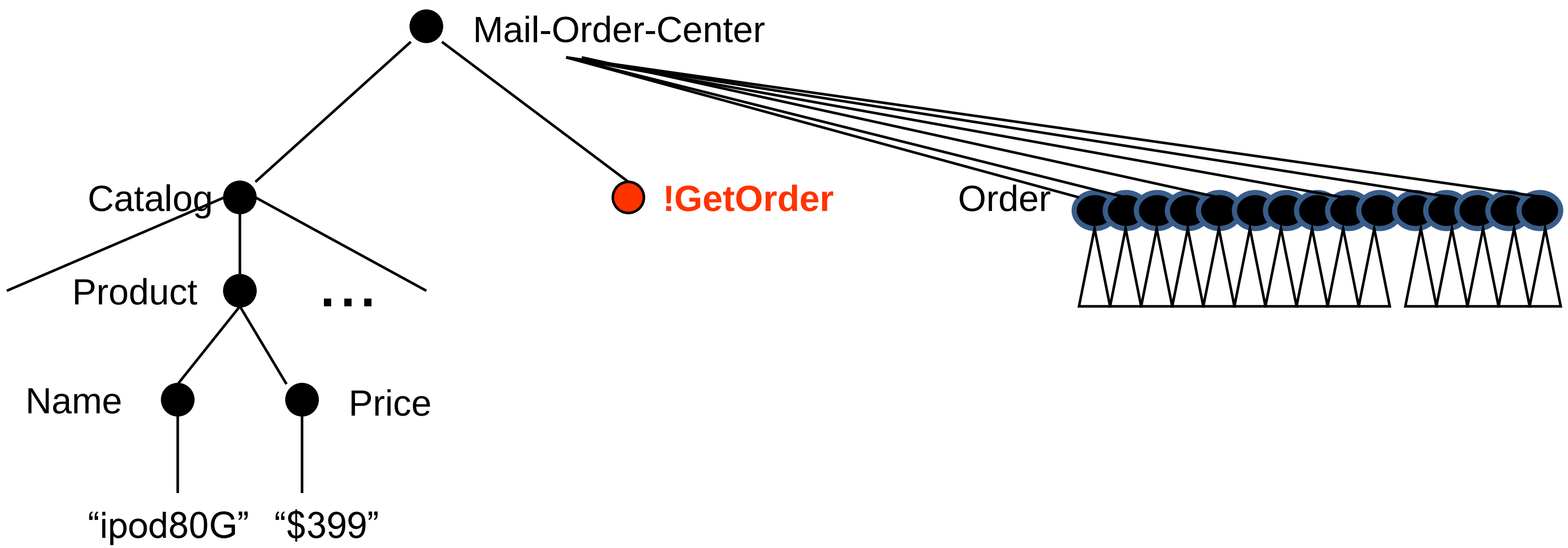
  restrict number of children with given tag, function symbol, or containing data values

- Data constraints

  Boolean combinations of tree patterns

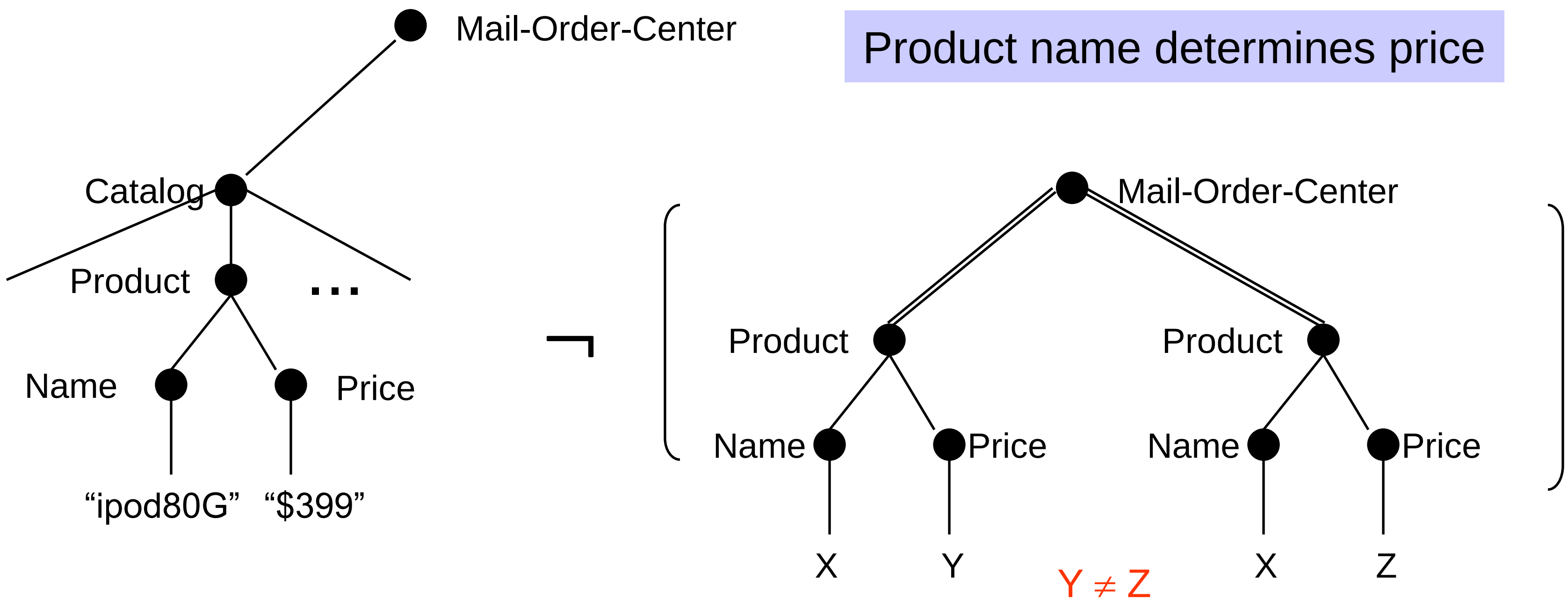
Static constraints on documents

- Example of data constraint



Static constraints on documents

- Example of data constraint



Function Guards and Queries

- call guards and return guards

  Boolean combinations of tree patterns
- argument and return queries

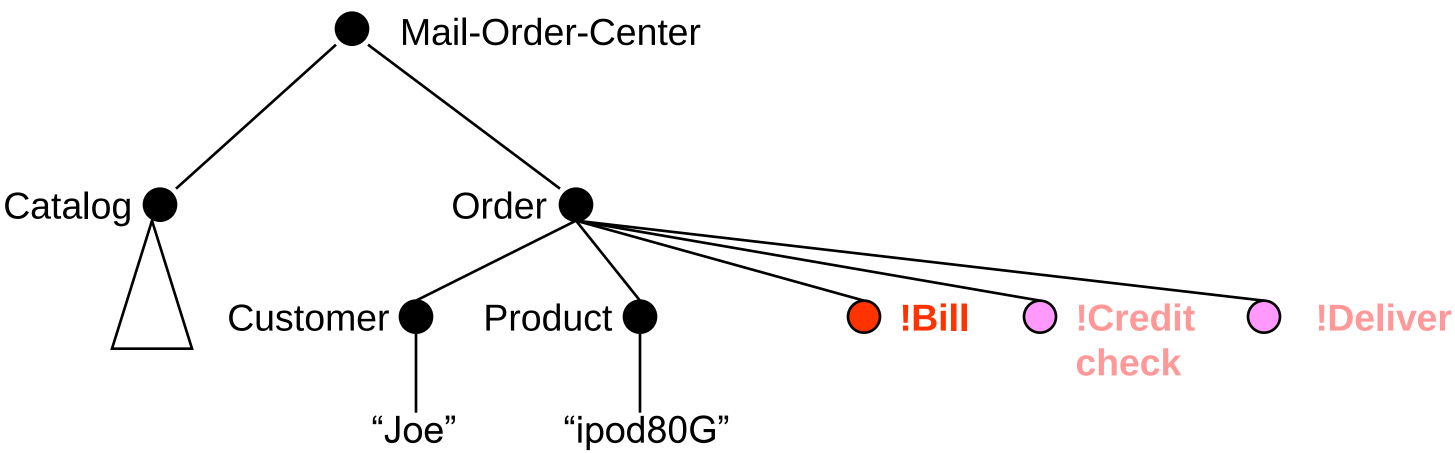
  similar to XML-QL

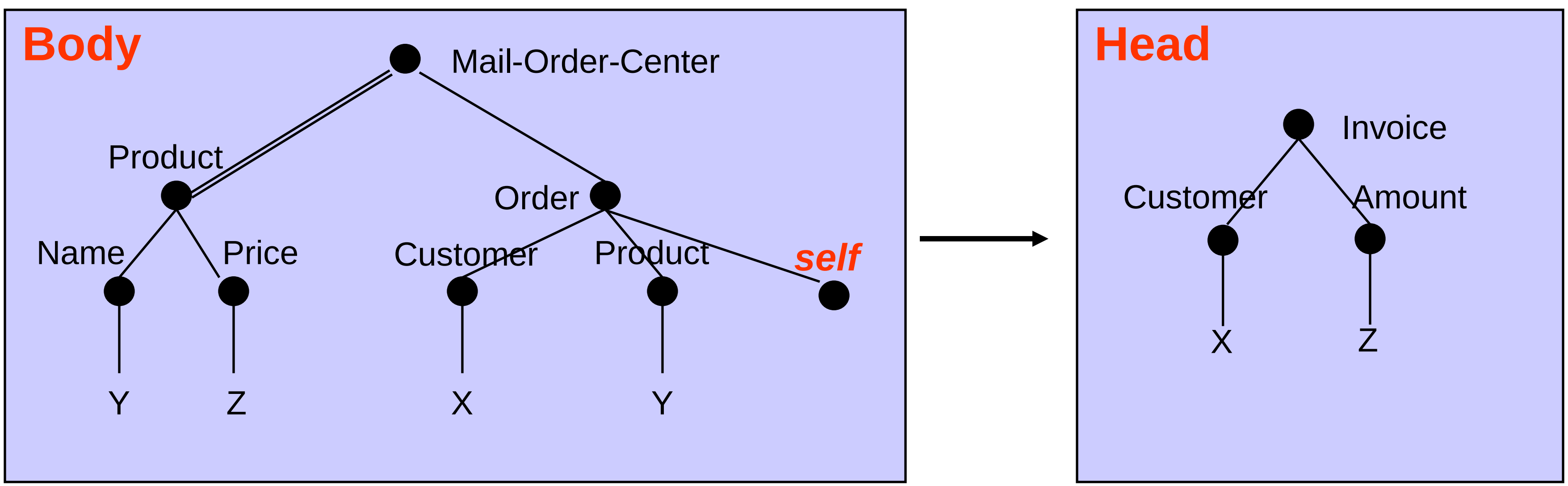
BODY → HEAD

collect variable bindings

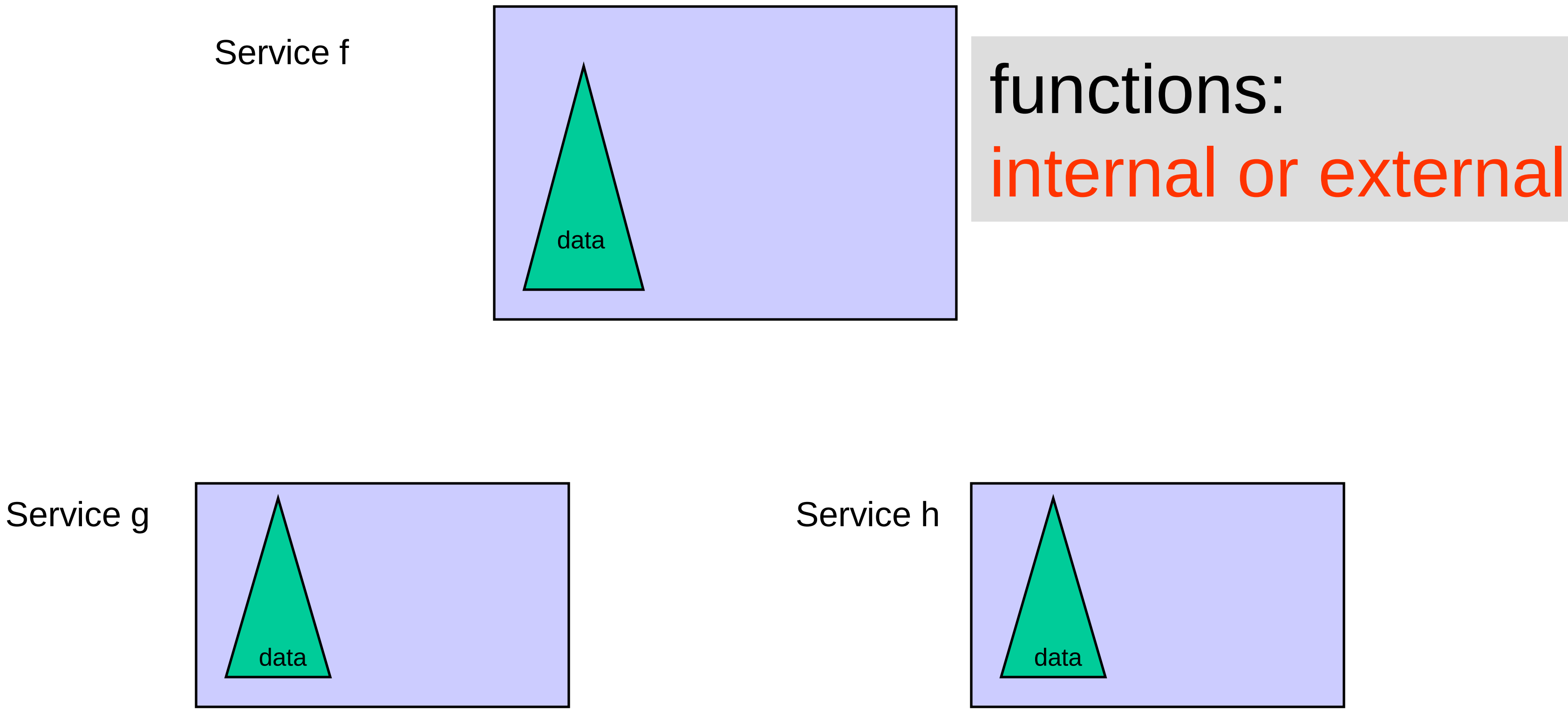
construct result

Example: argument query for **!Bill**



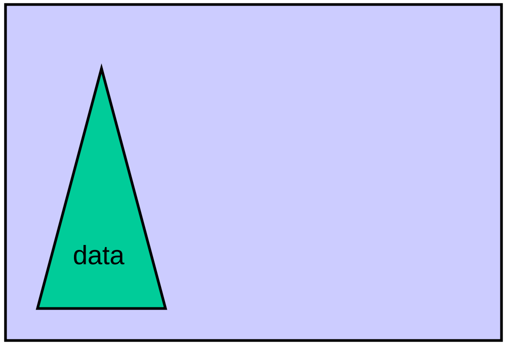


GAXML system: overall picture



GAXML system: overall picture

Service f



GAXML service specification:

- static constraints on trees

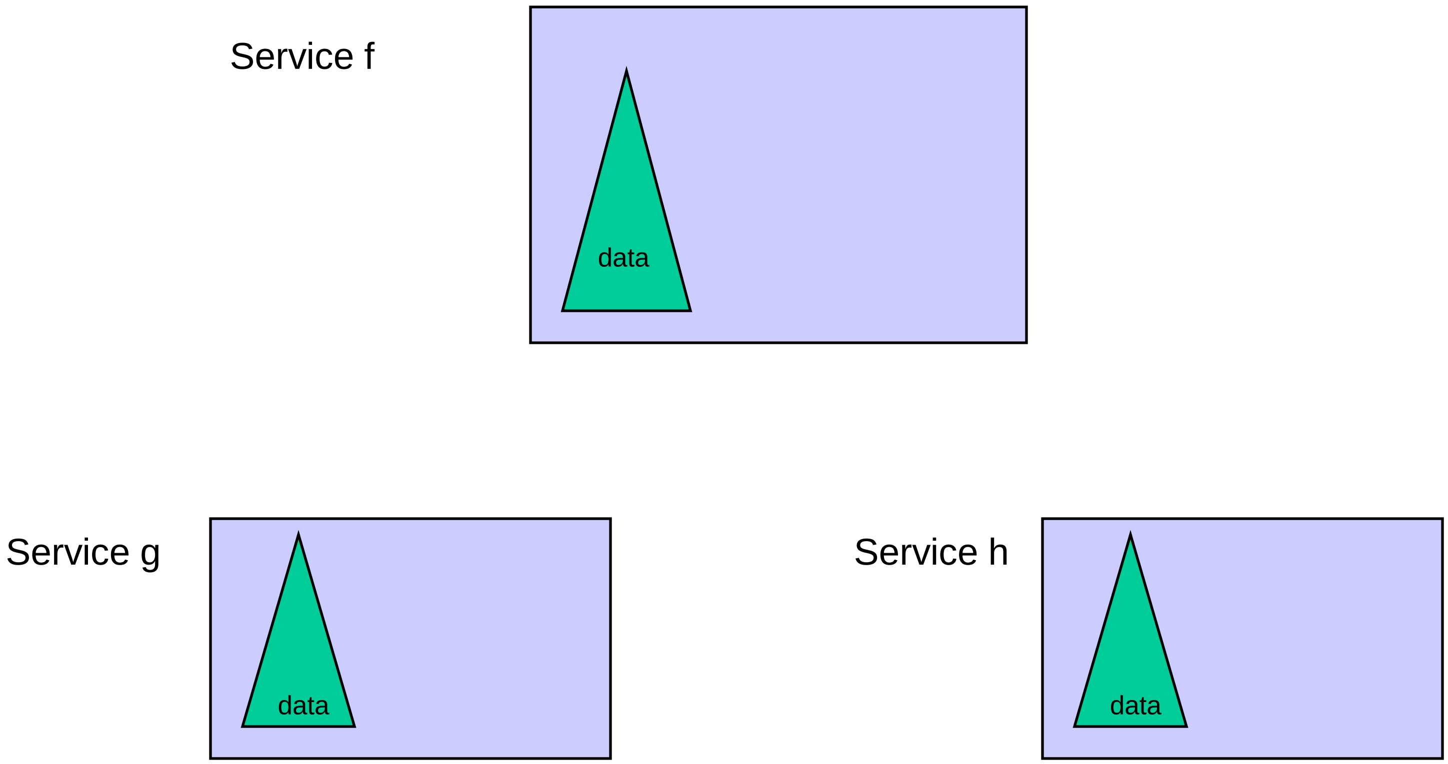
  DTDs and data constraints

- function definitions

  called functions: call guards, argument queries

  supported functions: return guards, return queries

Run of a GAXML system



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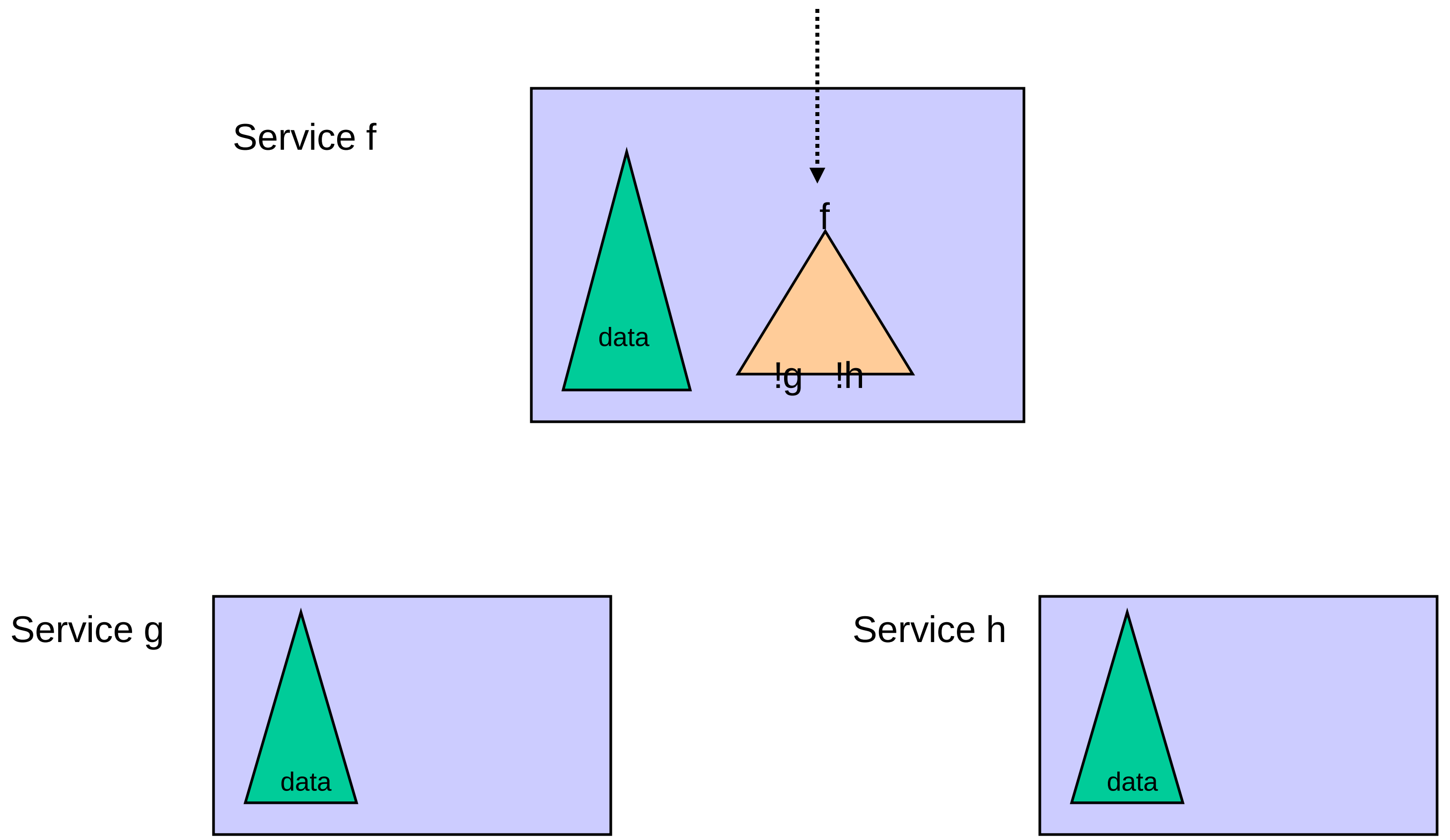

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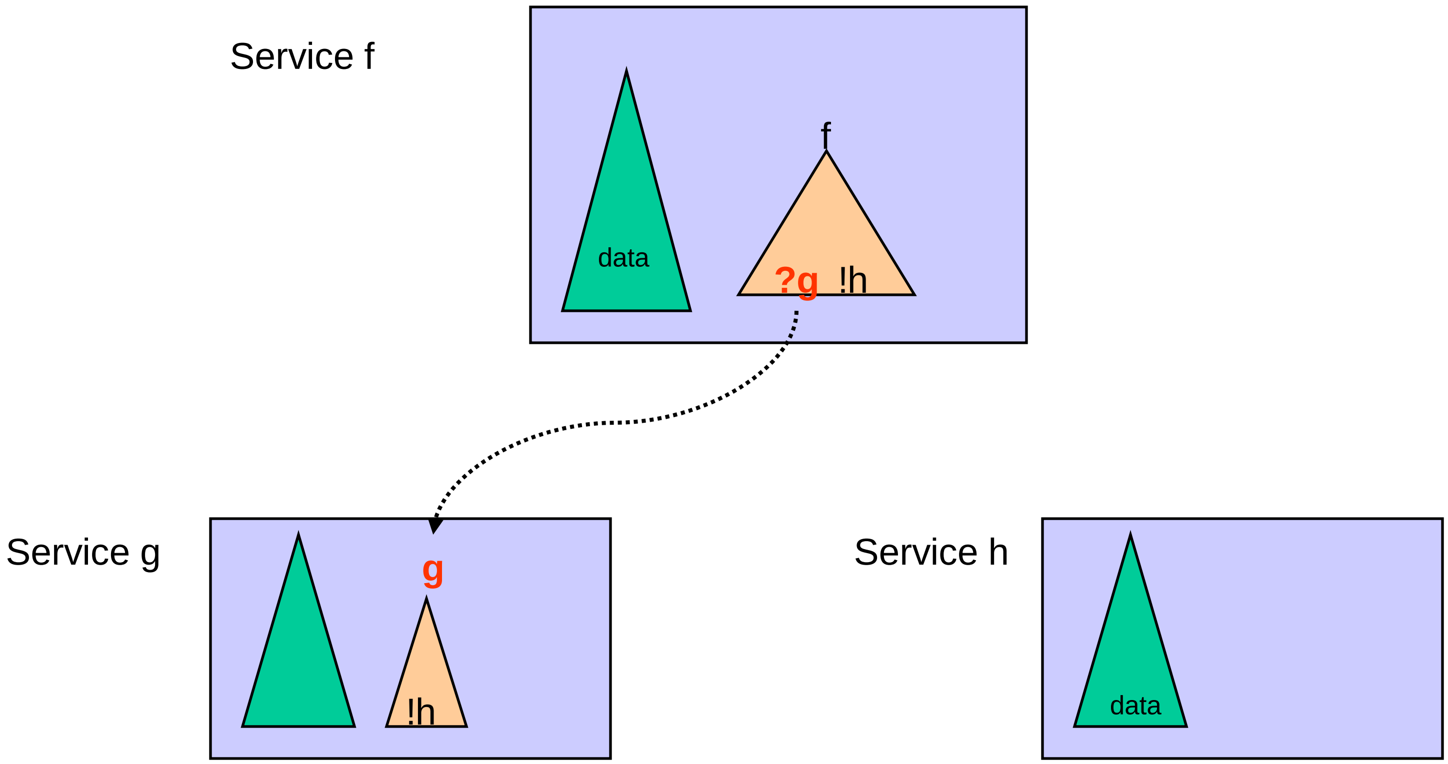

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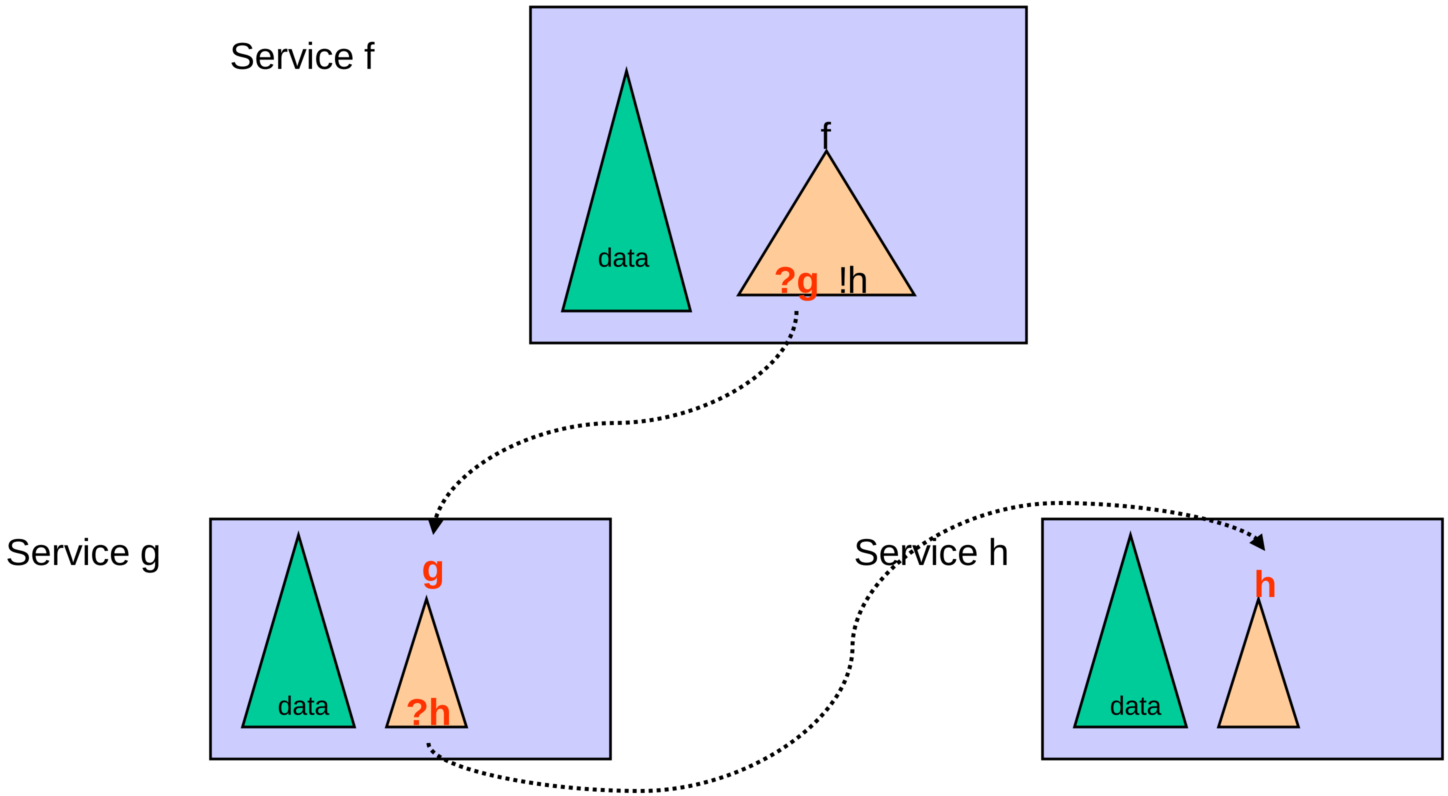

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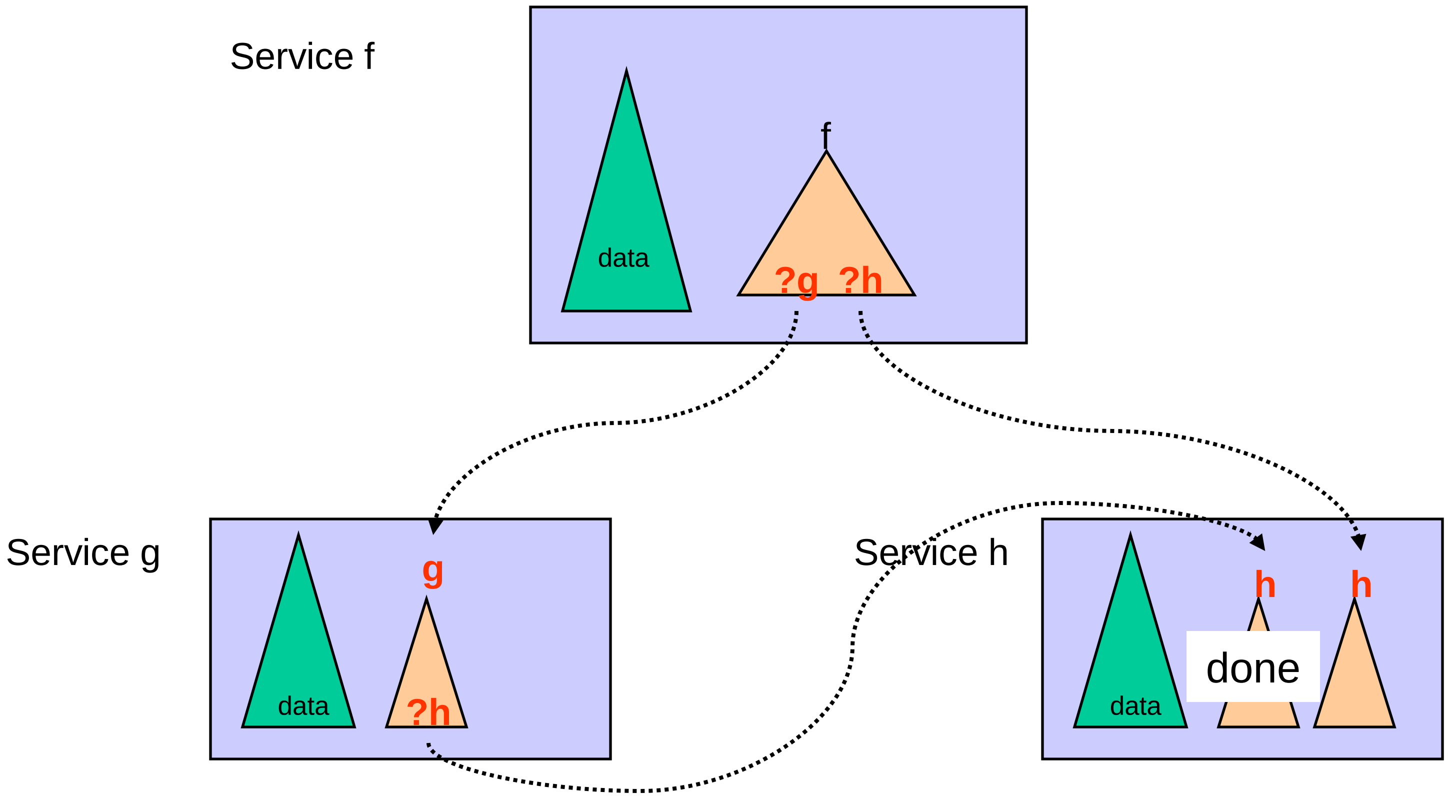

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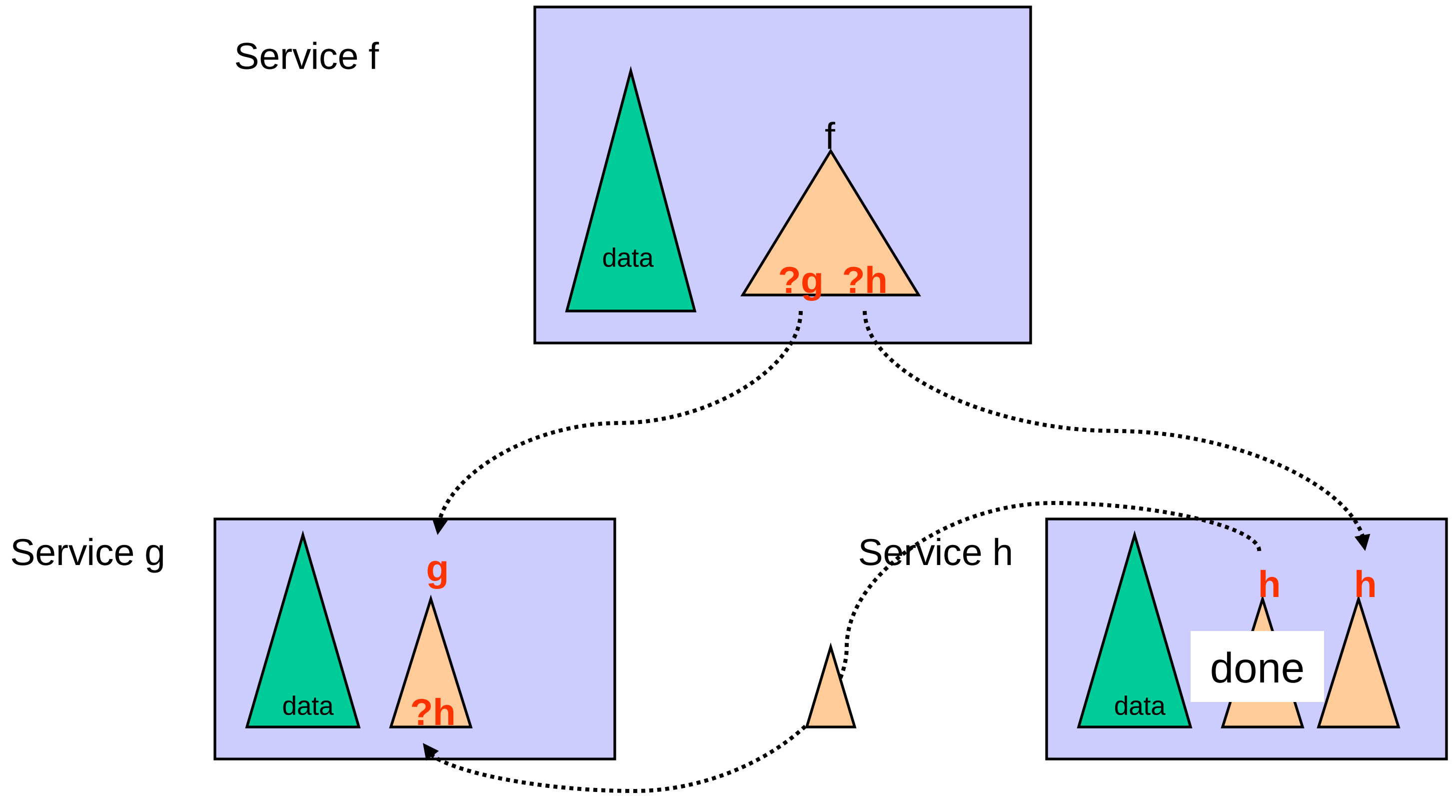

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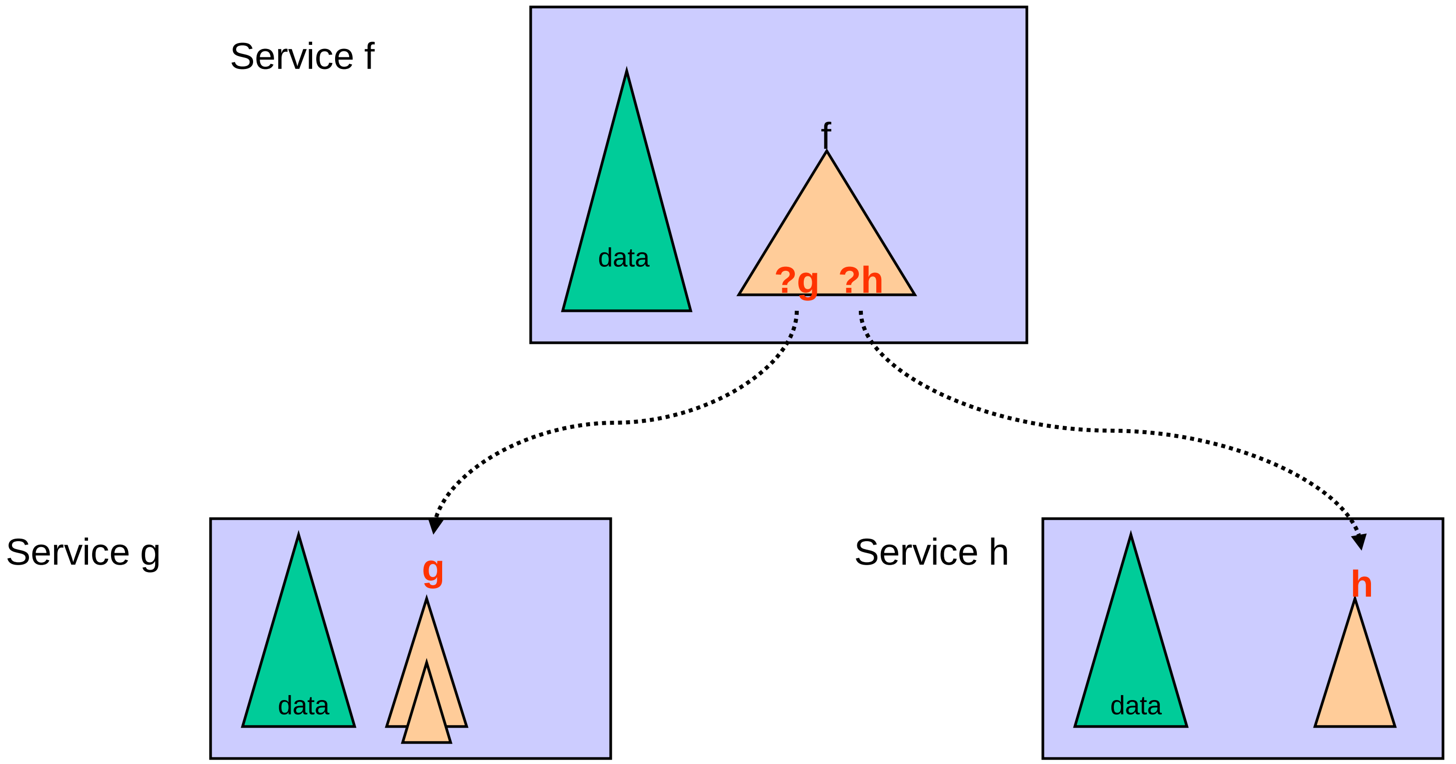

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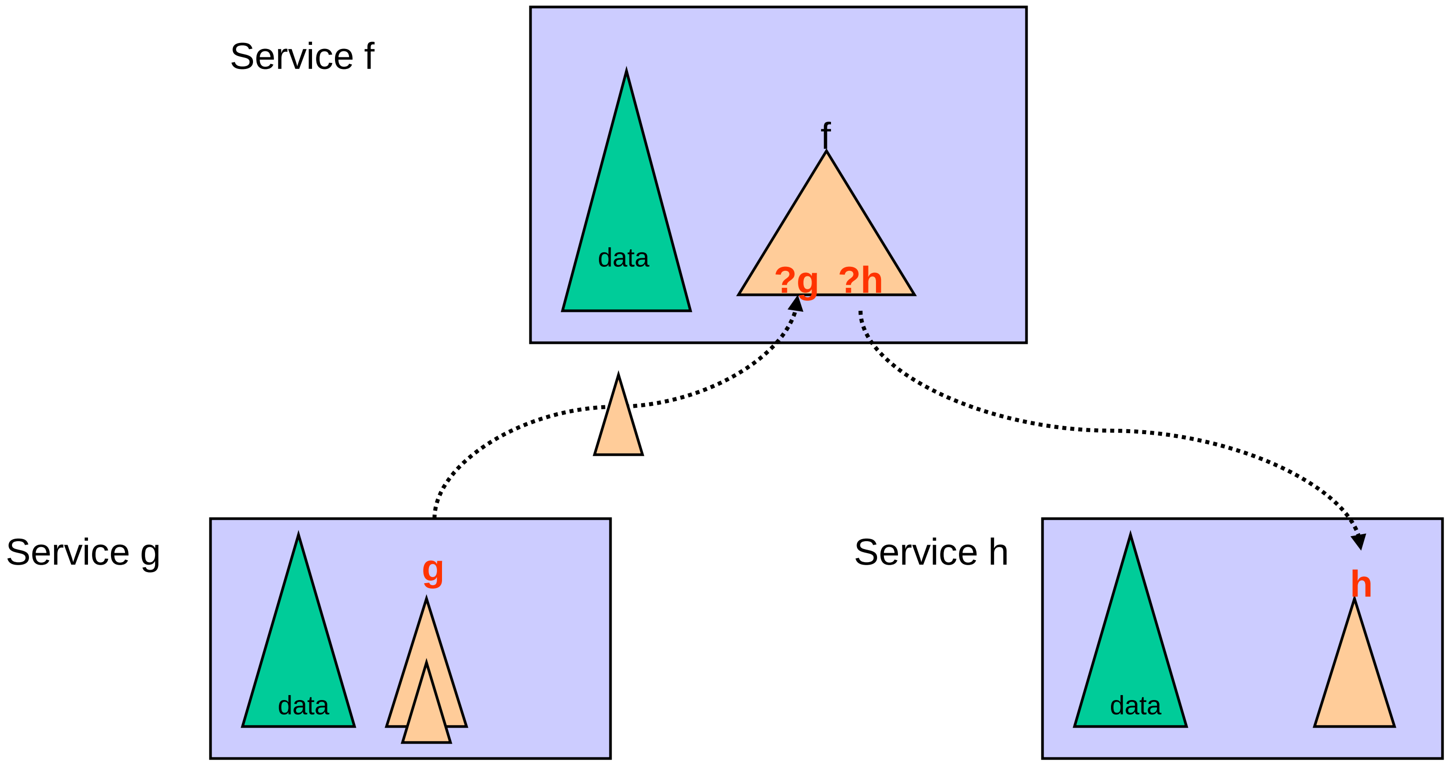

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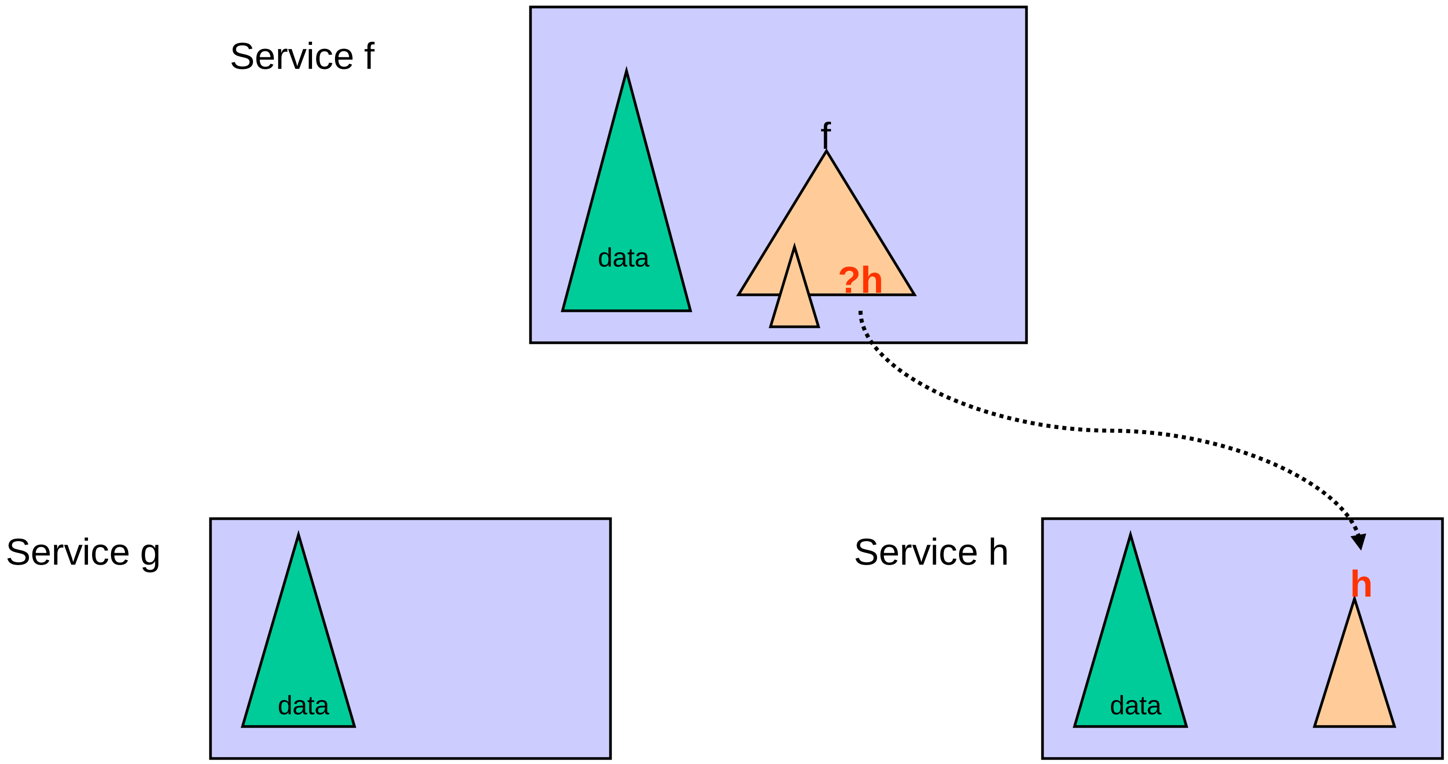

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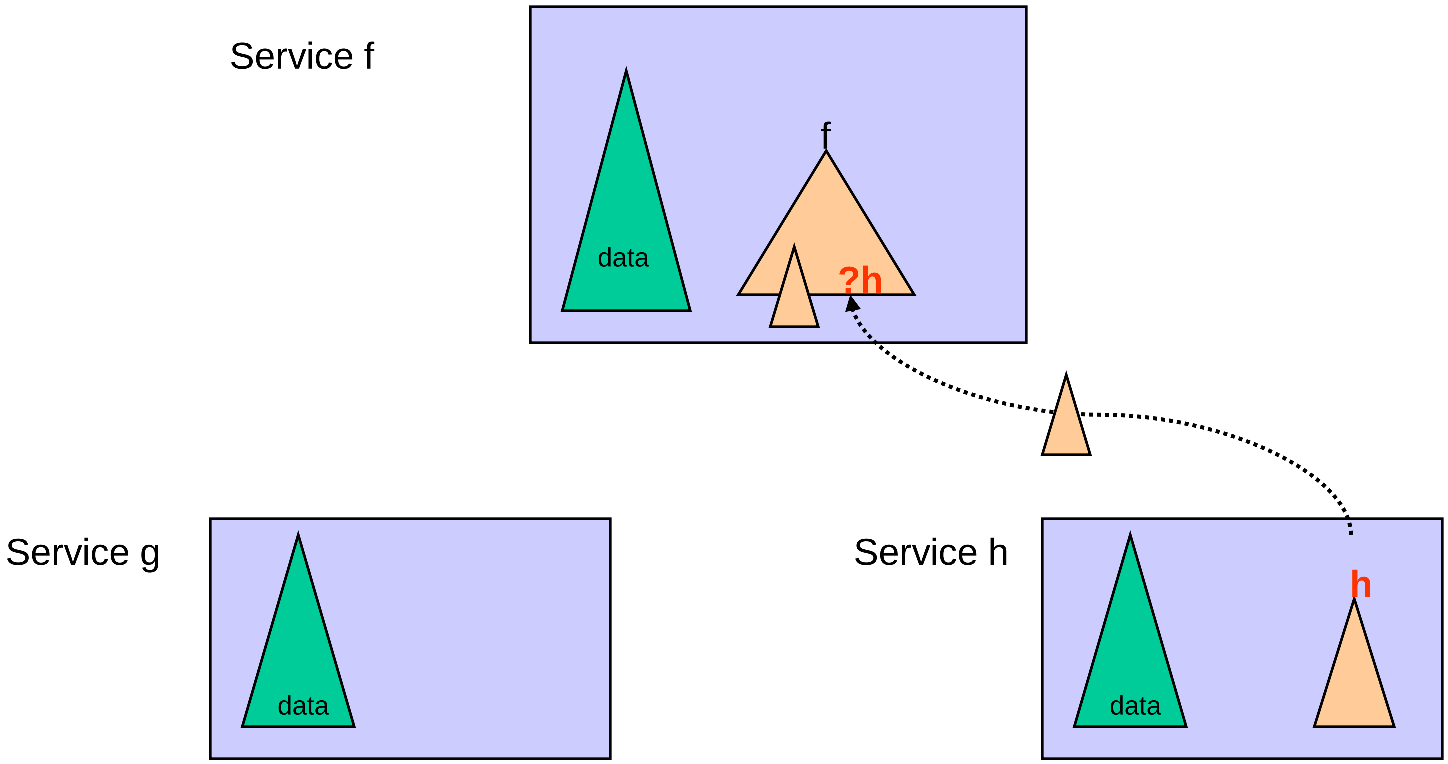

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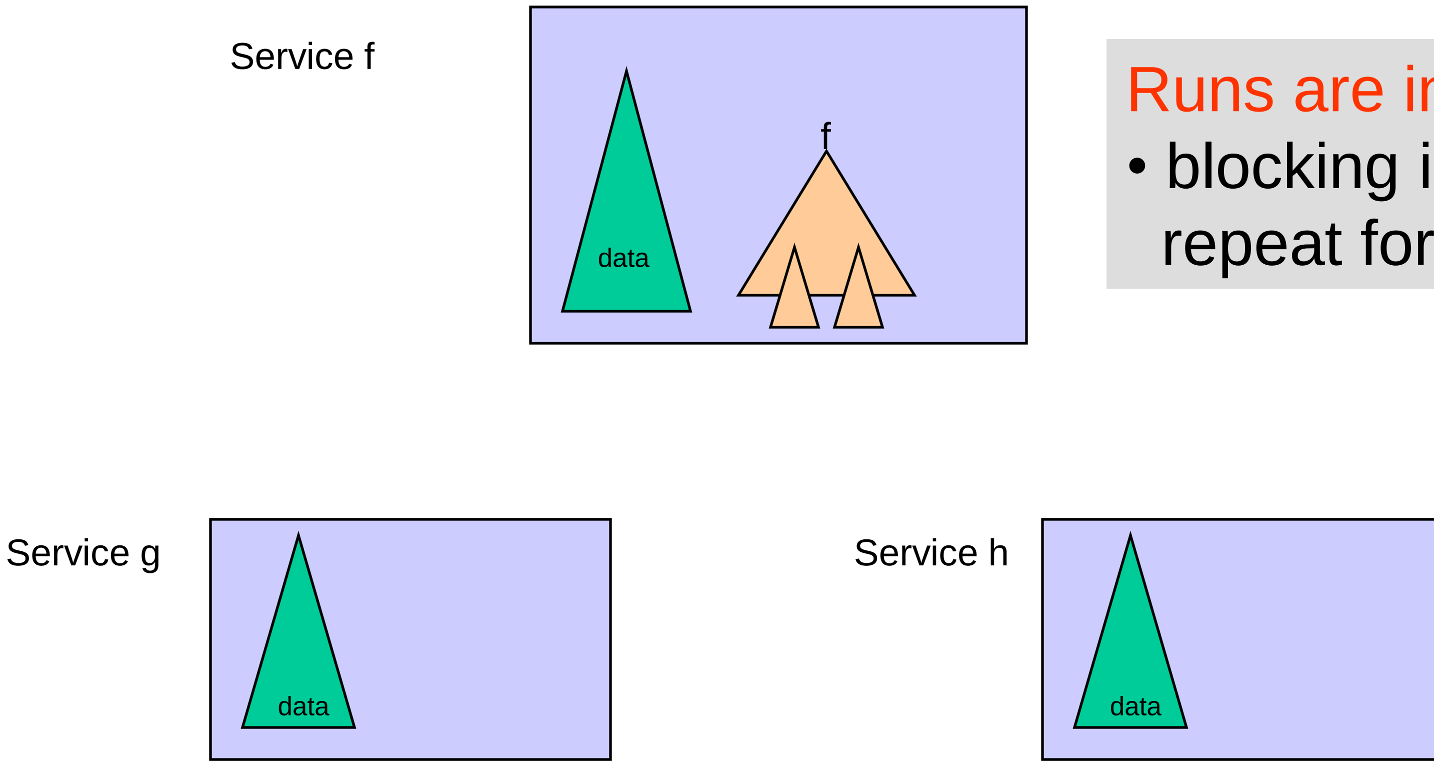


Runs are infinite

- blocking instances repeat forever

Specifying properties of runs: Tree-LTL

Linear-time temporal logic (LTL)

- propositions p,q,r, ...
- logical connectives: $\wedge$, $\vee$, $\neg$
- temporal operators:

G: always

F : eventually

U: until

X: next

Examples:

G p

G (p → **F** q)

GFp → **GF**q

From LTL to Tree-LTL

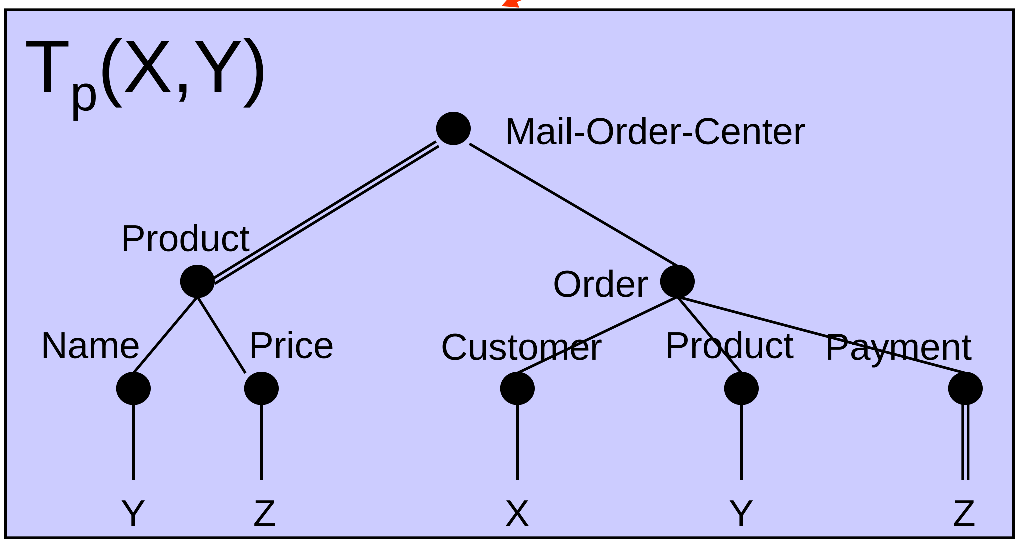
$\forall \overline{X} \; \forall \overline{Y}$ $\quad$ **G**(p $\rightarrow$ **F** q)

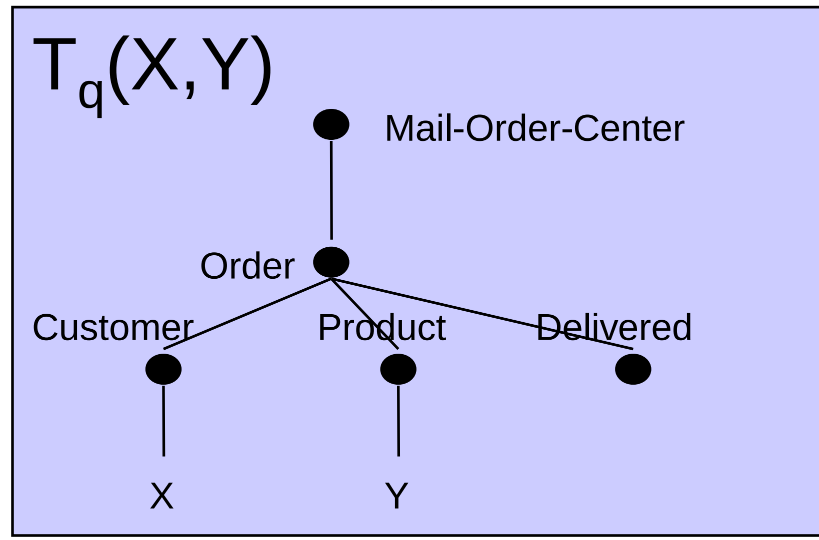
$T_p(\overline{X})$ $\quad$ $T_q(\overline{Y})$

tree patterns with free variables $\overline{X}$, $\overline{Y}$

From LTL to Tree-LTL

$\forall X \forall Y$ **G**(p → **F**q)





If a customer pays a product in the correct amount, the product is eventually delivered

Other examples of properties expressible in Tree-LTL

- no product is delivered unless it has been previously paid for in the correct amount
- the billed amount for a product is always the catalog price
- there are no two active orders by the same customer for the same product

Verification problem

Given a GAXML system S and a Tree-LTL formula φ, decide whether every run of S satisfies φ. If not, find a counterexample run.

Restriction for decidability:

non-recursiveness

syntactic restriction ensuring that every run reaches a blocking instance in a bounded number of steps

Main result

It is decidable whether a non-recursive GAXML system S satisfies a Tree-LTL formula φ

Note: still infinite-state system because of unbounded data! Use a “small run” property.

Complexity: CO-2NEXPTIME complete

- likely to be lower in many practical cases

-- CO-NEXPTIME if function call graph is a tree rather than a DAG

-- CO-NP with fixed bound on depth of trees, number of functions, and max number of variables in tree patterns

Other decidable problems for non-recursive GAXML systems

- successful termination

  does every run of S reach a blocking instance with no running function calls?

- typechecking

  if the initial instance of a run is valid, then all instances reachable in the run are also valid

valid: satisfy DTD and data constraints

Decidability with recursion

- Sufficient condition for safety with respect to Boolean combination of tree patterns φ

1. Every valid initial instance of G satisfies φ
2. If I satisfies φ and I → J, then J satisfies φ

complexity: CO-NEXPTIME

Decidability with recursion

- Bounded reachability of φ

For fixed k, is there an instance J of S that satisfies φ and is reachable by a run of length at most k ?

complexity: NEXPTIME

Conclusions

- Powerful framework for specifying evolving documents
- Tree-LTL can specify a wide range of useful properties
- Verification is decidable under the strong non-recursiveness restriction
- However, non-recursiveness is common in practice
- Even for recursive GAXML systems, one can isolate and verify meaningful non-recursive fragments

  Example:

  individual orders in the order processing system

Current and future work

- Extensions of verification results

  allow some recursion
- Connection to other workflow specification mechanisms
- Use AXML as a model for

  business artifacts

  influential IBM proposal for data-centric workflows

CO-2NEXPTIME upper bound

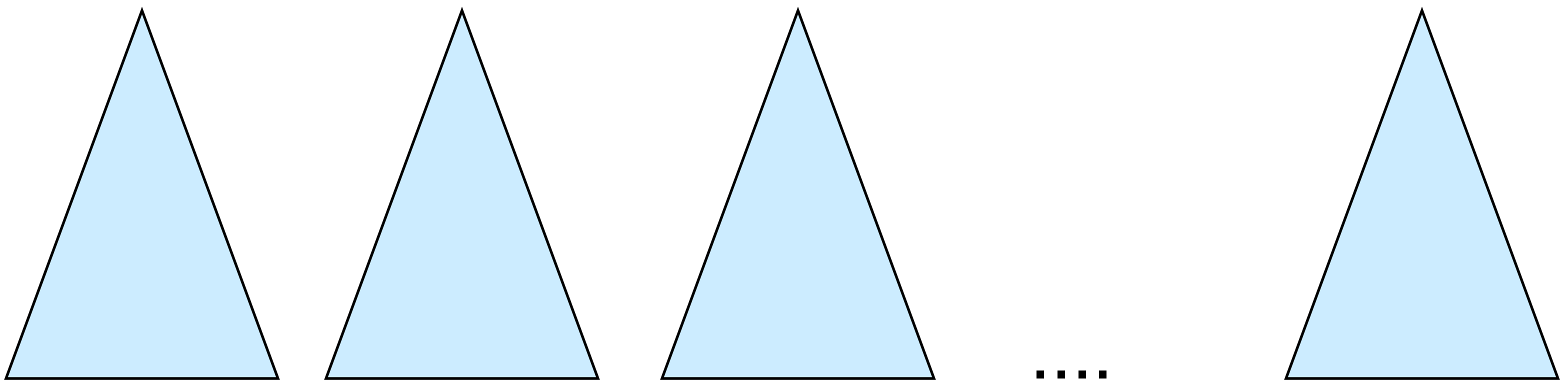
- Main idea: prove a "small run" property

If there is a run of S violating φ, then there is a "small run" of S violating φ

- size of "small run": exponential length, with instances doubly exponential in S and φ

Proof: reminiscent of small model property for $\exists^*\forall^*$ FO sentences

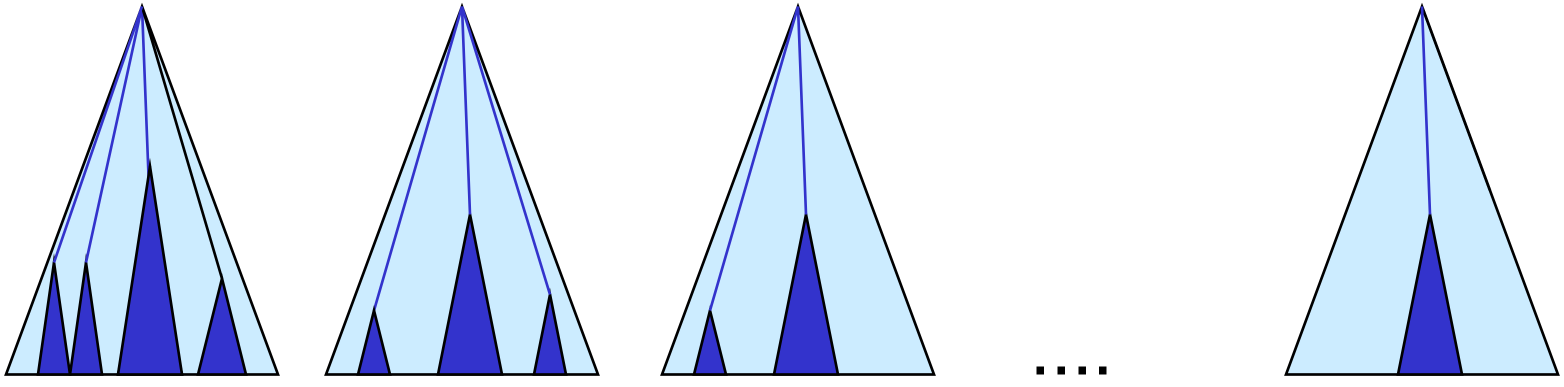
model built from witnesses to $\exists^*$ quantifiers



blocking run satisfying $\neg \varphi$

Proof: reminiscent of small model property for $\exists^*\forall^*$ FO sentences

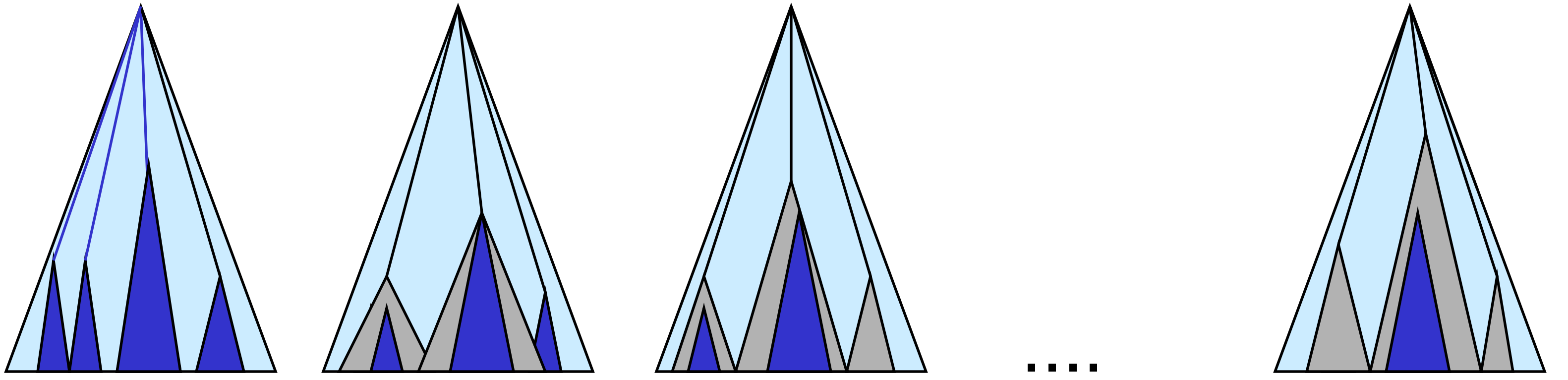
model built from witnesses to $\exists^*$ quantifiers



small run built in two stages: first collect witnesses needed to enable transitions and satisfy $\neg\varphi$

Proof: reminiscent of small model property for $\exists^*\forall^*$ FO sentences

model built from witnesses to $\exists^*$ quantifiers



then construct real run from witnesses

CO-2NEXPTIME lower bound

- Simulation of 2NEXPTIME Turing machine

2NEXPTIME Turing machine M and word w

↓

GAXML system S and Tree-LTL formula φ

S violates φ iff M accepts w

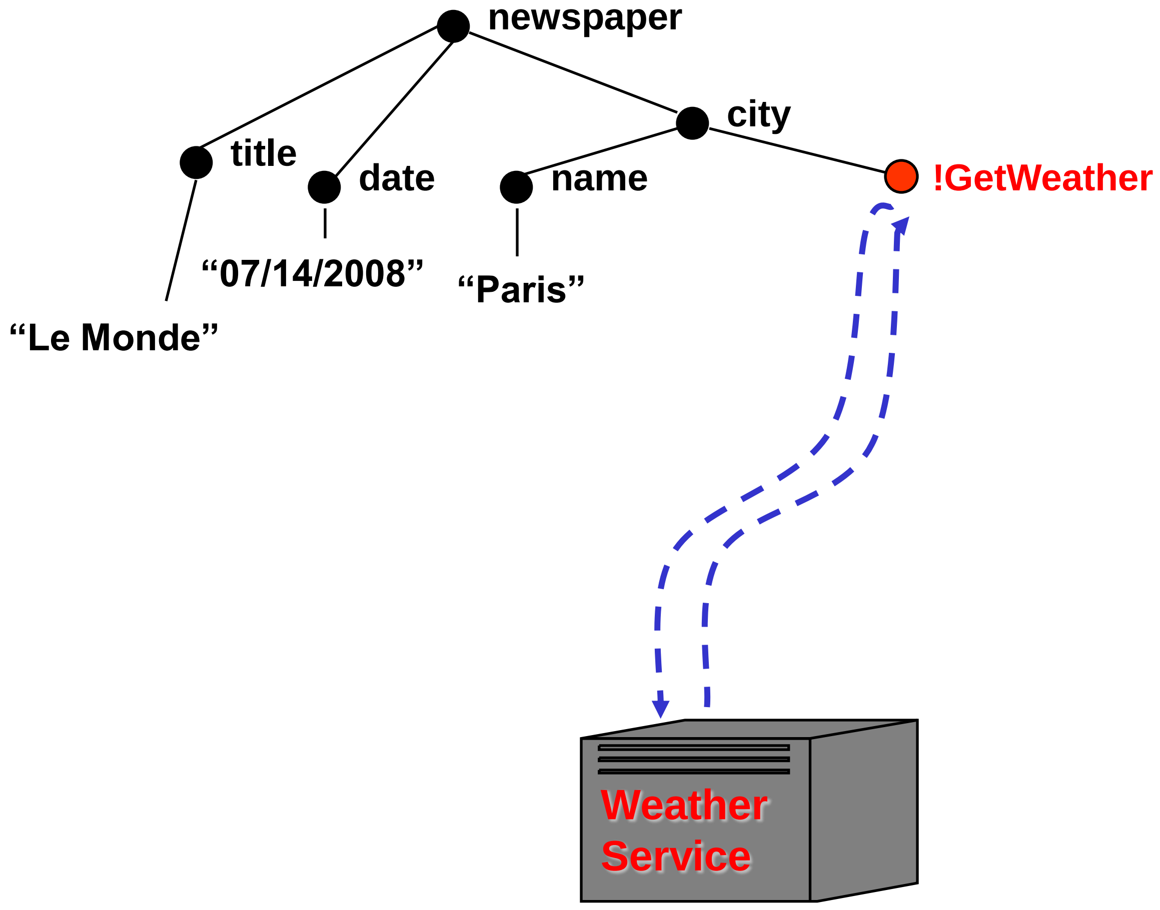
Non-trivial simulation:
tricky encoding and control needed

Non-recursive GAXML system

- acyclic function call graph
- no continuous functions
- non-recursive DTD
- DTD allows bounded number of function calls in each valid tree

Note: still infinite-state system!

Keeping dynamic data fresh



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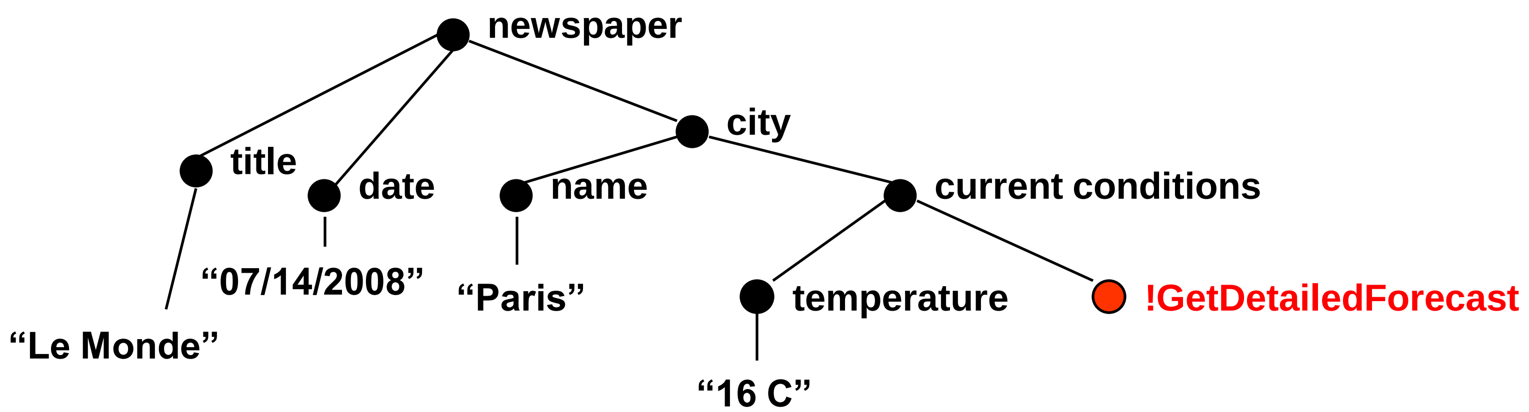

Example: argument query for **!Bill**