Transitions in Programming Models

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Significant Transitions

- Programming languages (PLs)
  - They evolve slowly and occasionally
  - But new *programming models* are invented routinely
    - As domain-specific libraries or API's
    - As program analysis tools
    - As language extensions
- Transitions
  - Significant transitions in programming models eventually "precipitate" into new programming languages (unpredictably)
  - We can watch out for significant transitions in programming models

New Programming Models

- We are in the middle of a transition in programming models (and eventually PLs)
  - More radical than C to C++
    - Brought more robust data structures (objects)
  - More radical than C++ to Java
    - Brought more robust control flows (strong typing)
- We now have a Cambrian explosion of programming models.
  - Lots of badly misshaped things are going to evolve before architectures settle down.
  - What's on the other side of the transition?

Transitions in 3 (related) areas

- A new emphasis on computation on WANs
  - Wide area data integration
    - XML is “net data”. ***XML API’s.***
    - Need to integrate this new data into PL data structures.
  - Wide area flow integration
    - Messages nor RPC, schedules not threads. ***Messaging API’s.***
    - Need to integrate these new flows into PL control constructs.
  - Wide area security integration
    - Access control, data protection. ***Security and privacy API’s.***
    - Need to integrate security properties into PL assertions.
- Impact
  - Disruptive transitions: not easy to convert these API’s into extensions of existing PLs.
  - Ideal topics for research.

Data Integration

- Wouldn't it be nice to "program directly against the schema" in a well-typed way?
  - PL data has traditionally been "triangular" (trees), while persistent data has traditionally been "square" (tables)
  - This has caused huge integration problems, known as the “impedence mismatch” in data base programming languages
  - Now, *BIG NEWS*, persistent data (XML) is triangular too!
  - New opportunity for PL integration
  - However, the type systems for PL data (based on tree matching) and XML (based on tree automata) are still deeply incompatible

Flow Integration

- Wouldn't it be nice to hide concurrency from programmers?
  - SQL does it well
  - UI packages do it fine
  - RPC does it ok
  - But we are moving towards more asynchrony, I.e. towards more visible concurrency (e-commerce scripts and languages, etc.)
  - *You can hide all concurrency some of the time, and you can hide some concurrency all the time, but you can't hide all concurrency all the time*
  - Asynchronous message-based concurrency does not fit easily with more traditional shared-memory synchronous concurrency control

Security Integration

- Wouldn't it be nice to have automatic security?
  - It's an applet. Sits is a sandbox. End of story.
  - Ok, what about *semi-automatic* security? Explicitly grant/require permissions. (Stack walking etc.)
  - Leads to emerging "sophisticated" access models that programmers do not understand reliably.

How to Integrate Transitions

- New programming models often require new kinds of analysis.
  - Domain Specific Languages: PLs equipped with specialized analysis for specific programming models
  - E.g. SQL (both data and concurrency optimization), security policy languages
- But some transitions go beyond DSL's
  - C++ was not just a DSL for objects, and Java was not just a DSL for type safety
  - Some transitions really require new "general-purpose" languages
  - We need more than an XML DSL, a messaging DSL, a security DSL

Reliability

- Whether or not we merge new programming models into PLs, we need analysis tools for these new situations
  - Data: e.g.: semistructured type/analysis systems
    - "Does the program output match the schema?"
  - Flow: e.g.: behavioral type/analysis system
    - "Does the program respect the protocol?"
  - Security: e.g.: information-flow type/analysis system
    - "Does the program defy policy or leak secrets"
- Analysis tools are critical for software reliability

What can we do about this?

- Assumptions
  - The existing situation is extremely messy
    - How many web services have you deployed lately?
  - Those 3 WAN-related transitions in programming models have a high probability of precipitating into new languages for WAN programming
- Research plan
  - In view of that, try to make some progress in one or more of those areas

Assorted Language-Related Advanced Activities
(Microsoft-centric)

- **Semistructured Data**
  - TQL, Spatial Data Types …
  - MS:*Xen* (Erik Meijer, Wolfram Shulte, Herman Venter, …)
    - Extends C# with XML-like data types and XML query expressions, integrated with real SQL queries.
- **Concurrent Flows**
  - BPEL, Polyphonic C#, Sharpie, Behavioral Types …
  - MS:*Highwire* (Greg Meredith, …)
    - Distributed scheduling language based on π-calculus and linear logic types.
- **Security/Privacy/Protocols**
  - Samoa, Vault …
  - MS:*Binder* (John DeTreville)
    - A Logic-Based security language

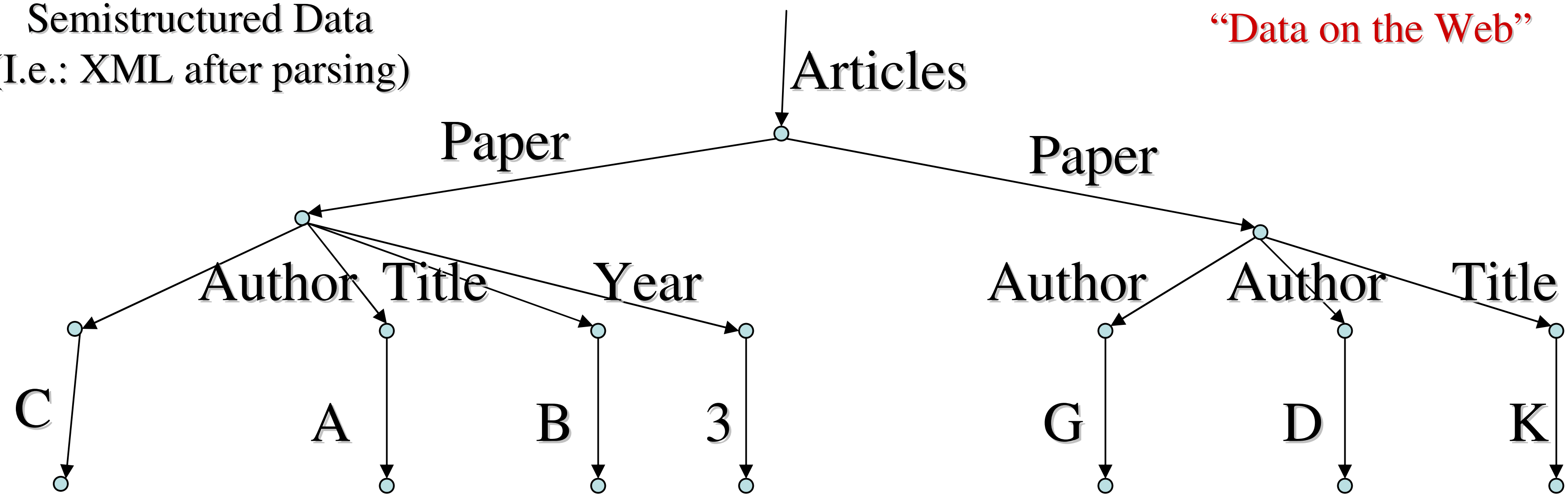
A Personal Agenda

- Data
  - Description logics (Spatial Logic)
  - Promising technology: Tree automata
- Flows
  - Polyphonic C#
  - Promising technology: Synchronization joins
- Hiding (a very small step towards security/privacy)
  - Trees with hidden labels
  - Promising technology: Name-dependent types

DATA

Abiteboul, Buneman, Suciu: "Data on the Web"

Semistructured Data
(I.e.: XML after parsing)



- A tree (or graph), unordered (or ordered). With labels on the edges.
- Invented for "flexible" data representation, for quasi-regular data like address books and bibliographies.
- Adopted by the DB community as a solution to the "database merge" problem: merging databases from uncoordinated (web) sources.
- Adopted by W3C as "web data", then by everybody else.

It's Unusual Data

- Not really arrays/lists:
  - Many children with the same label, instead of indexed children.
  - Mixture of repeated and non repeated labels under a node.
- Not really records:
  - Many children with the same label.
  - Missing/additional fields with no tagging information.
- Not really variants (tagged unions):
  - Labeled but untagged unions.
- Unusual data.
  - Yet, it aims to be the new universal standard for interoperability of programming languages, databases, e-commerce...

Needs Unusual Languages

- New *flexible* types and schemas are required.
  - Based on "regular expressions over trees" reviving techniques from tree-automata theory.
- New processing languages required.
  - Xduce [Pierce, Hosoya], Cduce, …
  - Various web scripting abominations.
- New query languages required. Various approaches:
  - From simple: Existence of paths through the tree.
  - To fuzzy: Is a tree "kind of similar" to another one?
  - To fancy: Is a tree produced by a tree grammar?
  - To popular: SQL for trees/graphs, for some value of "SQL".

Data Descriptions

- We want to *talk about* data
  - I.e., specify/query/constrain/typecheck the possible structure of data, for many possible reasons:
    - Typing (and typechecking): for language and database use.
    - Constraining (and checking): for policy or integrity use.
    - Querying (and searching): for semistructured database use.
    - Specifying (and verifying): for architecture or design documents.
- A *description* is a formal way of talking about the possible structure of data.
  - We go after a general framework: a very expressive language of descriptions.
  - Combining logical and structural connectives.
  - Special classes of descriptions can be used as types, schemas, constraints, queries, and specifications.

Example: Typing

Data

Cambridge[
  Eagle[
    chair[**0**] |
    chair[**0**]
  ]
]

In Cambridge there is (nothing but) a pub called the Eagle that contains (nothing but) two empty chairs.

Description

Cambridge[
  Eagle[
    chair[**0**] |
    T
  ] | **T**
]

In Cambridge there is (at least) a pub called the Eagle that contains (at least) one empty chair.

data matches description

Example: Queries

With match variables $\mathcal{X}$: *Who is really sitting at the Eagle?*

$$
\begin{array}{l}
\mathit{Eagle}[\\
\quad \mathit{chair}[\neg\mathbf{0} \wedge \mathcal{X}] \mid \\
\quad \mathbf{T} \\
]
\end{array}
$$

Yes: $\mathcal{X} = \mathit{John}[\mathbf{0}]$

Yes: $\mathcal{X} = \mathit{Mary}[\mathbf{0}]$

With *select-from*:

$\mathit{from}\ \mathit{Eagle}[...]$

$\mathit{match}\ \mathit{Eagle}[\mathit{chair}[\neg\mathbf{0} \wedge \mathcal{X}] \mid \mathbf{T}]$

$\mathit{select}\ \mathit{person}[\mathcal{X}]$

Single result:

$\mathit{person}[\mathit{John}[\mathbf{0}]] \mid$

$\mathit{person}[\mathit{Mary}[\mathbf{0}]]$

Example: Policies

"Vertical" implications about nesting

"Business Policy"

Borders[
Starbucks[…] |
Books[…]
]

Borders[**T**] ⇒
Borders[*Starbucks*[**T**] | **T**]

If it's a Borders,
then it must contain a Starbucks

"Horizontal" implications about proximity

"Social Policy"

Smoker[…] |
NonSmoker[…] |
Smoker[…]

(*NonSmoker*[**T**] | **T**) ⇒
(*Smoker*[**T**] | **T**)

If there is a NonSmoker,
then there must be a Smoker nearby

Example: Schemas

- Descriptions are a "very rich type system". We can comfortably represent various kinds of schemas.
- Ex.: Xduce-like (DTD-like) schemas:

0	the empty tree	
$\mathcal{A} \mid \mathcal{B}$	an $\mathcal{A}$ next to a $\mathcal{B}$	
$\mathcal{A} \vee \mathcal{B}$	either an $\mathcal{A}$ or a $\mathcal{B}$	
$n[\mathcal{A}]$	an edge n leading to an $\mathcal{A}$	
$\mathcal{A}^*$	$\triangleq \mu X.0 \vee (\mathcal{A} \mid X)$	the merge of zero or more $\mathcal{A}$s
$\mathcal{A}^+$	$\triangleq \mathcal{A} \mid \mathcal{A}^*$	the merge of one or more $\mathcal{A}$s
$\mathcal{A}^?$	$\triangleq 0 \vee \mathcal{A}$	zero or one $\mathcal{A}$

Current Work

- **Longer-term research:**
  - **Powerful languages of data description, based on *spatial logics*. Akin to *description logics* of some time ago, but seen as type systems.**
  - **Special cases are regular expressions over trees (XML query, etc.)**
  - **Lots of open problems in this area (typing and subtyping algorithms)**

Xen Type System Extensions

(structural)

```
T ::= N
   |  T[] | T{}
   |  T(…,T,…)
   |  T|T
   |  T*
   |  […, T m,…]
```

arrays

closures

union

streams

tuples (rows)

FLOWS

- Distribution => concurrency + latency
  => asynchrony
  => more concurrency
- Approaches: Message-passing, event-based programming, dataflow models
- Languages: coordination (orchestration) languages, workflow languages

Language Support for Concurrency

- Make invariants and intentions more apparent (part of the interface)
- Good software engineering
- Allows the compiler much more freedom to choose different implementations
- Also helps other tools

.NET today

- Java-style “monitors”
- OS shared memory primitives
- Delegate-based asynchronous calling model
- Hard to understand, use and get right
  - Different models at different scales
  - Support for asynchrony all on the caller side – little help building code to *handle* messages (must be thread-safe, reactive, and deadlock-free)

Polyphonic C#

- An extension of the C# language with new concurrency constructs
- Based on the join calculus
  - A foundational process calculus like the π-calculus but better suited to asynchronous, distributed systems
  - First applied to functional languages (JoCaml).
  - It adapts remarkably well to o-o classes and methods.
- A single model which works both for
  - local concurrency (multiple threads on a single machine)
  - distributed concurrency (asynchronous messaging over LAN or WAN)
- It is different. But it's also a simple extension of familiar o-o notions.

In one slide:

- Objects have both synchronous and *asynchronous* methods.
- Values are passed by ordinary method calls:
  - If the method is synchronous, the caller blocks until the method returns some result (as usual).
  - If the method is async, the call completes at once and returns void.
- A class defines a collection of *chords* (synchronization patterns), which define what happens once a particular *set* of methods have been invoked. One method may appear in several chords.
  - When pending method calls match a pattern, its body runs.
  - If there is no match, the invocations are queued up.
  - If there are several matches, an unspecified pattern is selected.
  - If a pattern containing *only* async methods fires, the body runs in a new thread.

A simple buffer

```
class Buffer {
  String get() & async put(String s) {
     return s;
  }
}
```

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- An asynchronous method (hence returning no result), with a string argument

A simple buffer

```
class Buffer {
  String get() & async put(String s) {
     return s;
  }
}
```

- An ordinary (synchronous) method with no arguments, returning a string
- An asynchronous method (hence returning no result), with a string argument
- Joined together in a chord

A simple buffer

```
class Buffer {
  String get() & async put(String s) {
    return s;
  }
}
```

- Calls to `put()` return immediately (but are internally queued if there's no waiting `get()`).
- Calls to `get()` block until/unless there's a matching `put()`
- When there's a match the body runs, returning the argument of the `put()` to the caller of `get()`.
- Exactly which pairs of calls are matched up is unspecified.

A simple buffer

```
class Buffer {
  String get() & async put(String s) {
    return s;
  }
}
```

- Does example this involve spawning any threads?
  - No. Though the calls will usually come from different pre-existing threads.
- So is it thread-safe? You don't seem to have locked anything…
  - Yes. The chord compiles into code which uses locks. (And that *doesn't* mean everything is synchronized on the object.)
- Which method gets the returned result?
  - The synchronous one. And there can be at most one of those in a chord.

Reader/Writer

…using threads and mutexes in Modula 3

An introduction to programming with threads. Andrew D. Birrell, January 1989.

```
VAR i: INTEGER;
VAR m: Thread.Mutex;
VAR c: Thread.Condition;

PROCEDURE AcquireExclusive();
BEGIN
    LOCK m DO
        WHILE i # 0 DO Thread.Wait(m,c) END;
        i := -1;
    END;
END AcquireExclusive;

PROCEDURE AcquireShared();
BEGIN
    LOCK m DO
        WHILE i < 0 DO Thread.Wait(m,c) END;
        i := i+1;
    END;
END AcquireShared;

PROCEDURE ReleaseExclusive();
BEGIN
    LOCK m DO
        i := 0; Thread.Broadcast(c);
    END;
END ReleaseExclusive;

PROCEDURE ReleaseShared();
BEGIN
    LOCK m DO
        i := i-1;
        IF i = 0 THEN Thread.Signal(c) END;
    END;
END ReleaseShared;
```

An integer i represents the lock state:

-1	←→	0	←→	1	←→	2	←→	3 …
(exclusive)		(available)		(shared)				

Reader/Writer in five chords

```
public class ReaderWriter {
  public void AcquireExclusive() & async Idle() {}
  public void ReleaseExclusive() { Idle(); }

  public void AcquireShared() & async Idle()    { S(1); }
  public void AcquireShared() & async S(int n) { S(n+1); }
  public void ReleaseShared() & async S(int n) {
    if (n == 1) Idle(); else S(n-1);
  }

  public ReaderWriter() { Idle(); }
}
```

A single private message represents the state:

none ←→ `Idle()` ←→ `S(1)` ←→ `S(2)` ←→ `S(3)` …

(exclusive) (available) (shared)

A pretty transparent description of a simple state machine, as it should be.

Features

- **A clean, simple, new model for asynchronous concurrency in C#**
  - Declarative, local synchronization
  - Model good for both local and distributed settings
  - Efficiently compiled to queues and automata
  - Easier to express and enforce concurrency invariants
  - Compatible with existing constructs, though they constrain our design somewhat
  - Minimalist design – pieces to build whatever complex synchronization behaviours you need
  - Solid foundations
  - Works well in practice
  - Convenient - much better than programming state machines yourself

Implementation

- Translate Polyphonic C# to C#
- Introduce queues for pending calls (holding blocked threads for sync methods, arguments for asyncs)
- Efficient – bitmasks to look for matches

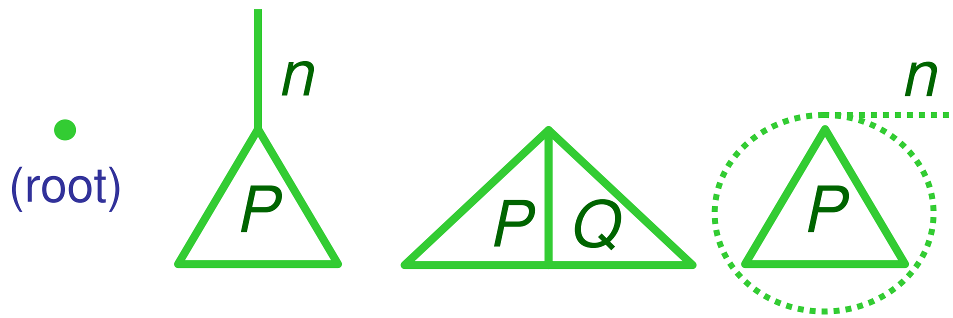
HIDING

- Any kind of security/privacy issue has to do with hiding something
  - Hiding information by encryption
  - Hiding information by access control
  - Hiding private data so it does not escape
- Baby step:
  - How can we support hidden data in a programming language?
  - N.B.: Hiding *pure names* (passwords/ids) not, e.g., hiding numbers

Data Model: Trees with Hidden Labels

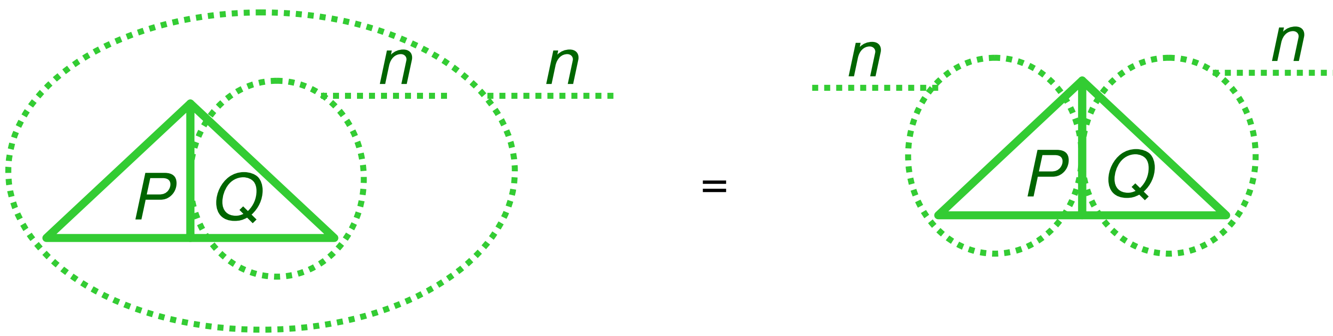
P*,*Q **::=**

- **0**
- ***n*[*P*]**
- ***P* | *Q***
- **(ν*n*)*P***

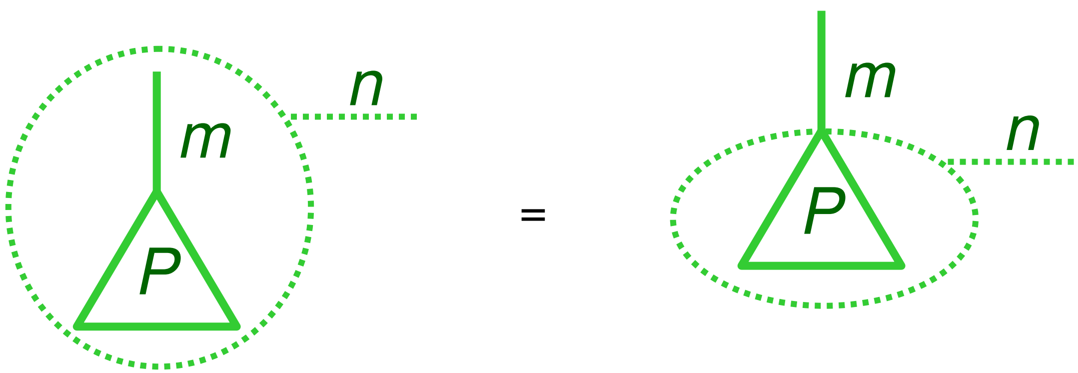


Tree Equivalence (Structural Congruence)

- $(\nu n)(P \mid (\nu n)Q) \equiv ((\nu n)P) \mid ((\nu n)Q)$

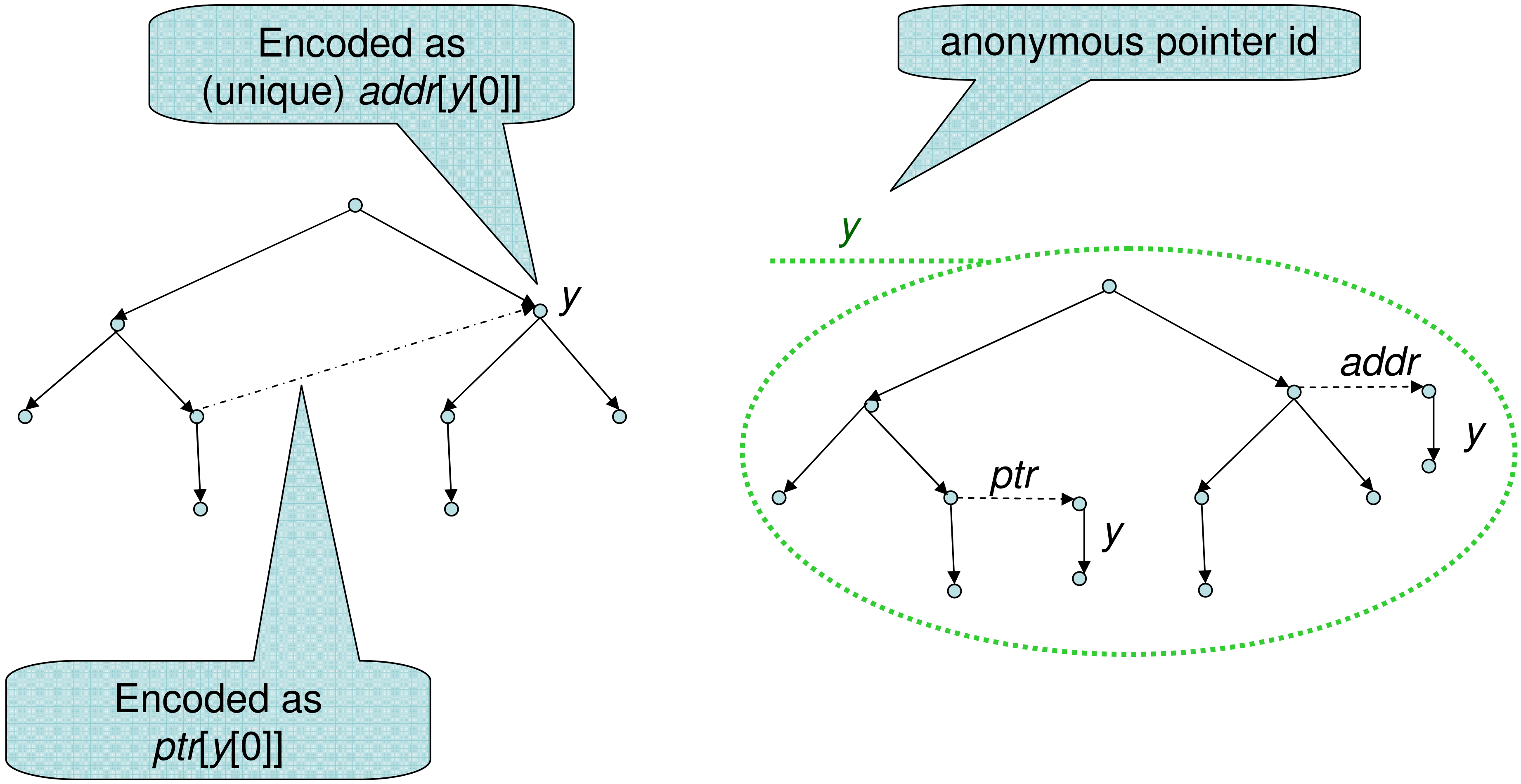


- $(\nu n)m[P] \equiv m[(\nu n)P]$ if $n \neq m$

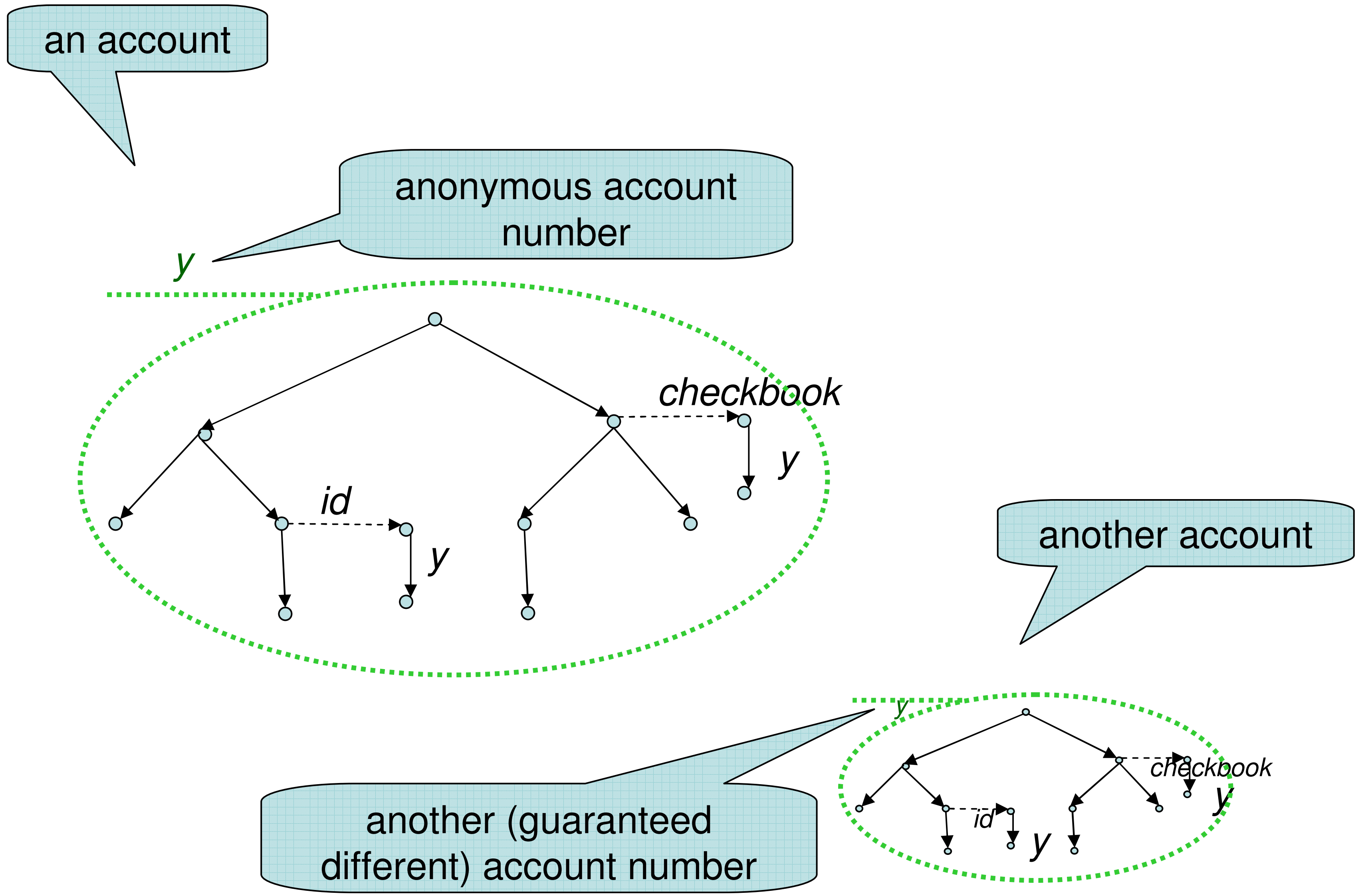


Ex: Local Pointers

- **E.g., XML IDREFs**



Ex: Unique and Unguessable IDs



Type Systems for Hidden Names

- *account* : H*y*. … *id*[*y*] … *checkbook*[*y*] …

- These are *name-dependent* types
  - Dependent types: traditionally very hard to handle because of computational effects.
  - But dependent only on "pure names": no computational effects.
  - Name-dependent types are emerging as a general techniques for handling freshness, hiding, protocols (e.g. Vault), and perhaps security/privacy aspects in type systems.

Conclusions

- **New languages**
  - **Language evolution is driven by wishes.**
  - **Language adoption is driven by needs.**
- **We now *badly need* evolution in areas related to WAN-programming.**
  - **Lots of inelegant need-driven *hacks*.**
  - **Some interesting *designs* here and there.**
  - **Let's put them together into *languages* that are useful for wide-area programming!**

References

- Data
  - Meijer *et al.*: Xen
  - Cardelli, Ghelli *et al.*: TQL
- Flows
  - Fournet *et al.*: Join Calculus
  - Benton, Cardelli, Fournet: Polyphonic C#
  - Larus *et al*: Behave!
- Hiding/Freshness
  - Pitts *et al*: Fresh-ML
  - Cardelli, Gardner, Ghelli: Manipulating Trees with Hidden Labels.
  - DeLine *et at*: Vault

(See personal web pages or search engines.)