The essence of data access in Cω

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Summary of talk

1. Background

   What's the problem? Why another programming language? What's new?

2. Introduction to Cω

   Informal introduction

3. Formalization

   (Very briefly) Type system; operational semantics; breaking news

4. Related work
5. Conclusions

What’s the problem?

- Many typical web-based applications need to
  - create/read relational data
  - create queries to be executed on a database server
  - create/read semistructured data (XML/HTML)
  - deal with inherent (asynchronous) concurrency
- Leads to three-tier software architecture

Can't I do this in Java/C# already?

- Relational Data/Queries:
  - Use APIs to create/access relational data (relational data as objects)
  - Use APIs to create queries (queries as strings)
- Semistructured data:
  - As above:
    - SS data as objects
    - Queries as strings
- Upper and lower tiers are very fragile ☹
- (Asynchronous) concurrency:
  - As many APIs as there are concepts!

Guiding principle

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Put features in the language itself, rather than in libraries

- Provide better level of abstraction
- Make invariants and intentions more apparent (part of the interface)
- Give stronger compile-time guarantees (types)
- Enable different implementations and optimizations
- Expose structure for other tools to exploit (example: static analysis)

Part I: A Cω primer

Design brief

- Take C# as a starting point (warts and all)
- No changes to the semantics of C#
- No changes to the CLR (1.1)
- Minimal extensions:
  - Don’t simply tack on the entire relational and semi-structured data models
  - Rather offer similar expressive power, but more in the spirit of an object-oriented language
  - XML literals and (some fragment of) SQL

Cω (partial) castlist

- Data access extensions:
  - Originally the brainchild of Erik and Wolfram


- Concurrency:
  - Due to Nick Benton, Luca Cardelli and Cédric Fournet
  - aka “Polyphonics”
- Compiler gurus:
  - Herman Venter, Claudio Russo and others

What's been added to C#?

- Data access:
  - New types
    - Streams
    - Anonymous structs
    - Choice types
    - Content classes
  - Generalized member access
  - XML literals
  - SQL expressions
- Concurrency:
  - New type
    - **`async`**
  - Generalized notion of method header to define chords

Described at ECOOP 2002!

New type #1: Streams

- New type: **`T*`** (sequence of **`T`**)
- Close relative of **`IEnumerable<T>`** (C# 2.0)
- Streams generated by statement blocks that **`yield`** values
- Streams consumed by **`foreach`** loop
- No nested streams (no **`T**`**)
  - Just like in XQuery/XPath

Example stream processing

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```
public static int* FromTo(int s, int e)    {
      for (i = s; i <= e; i++) yield return i;
}

int* OneToTen = FromTo(1,10);

foreach(int j in OneToTen) {
      Console.WriteLine(j);
}
```

Note the co-routine like behaviour

New type #2: Anonymous structs

- New type:

```
struct{int i; string s; string s;}
```

- Constructed in obvious way:

```
struct{int i; string s; string s;} tup =
          new{i=42, s="Erik", s="Wolfram"};
```

- (Like ML records but ordered, duplicates allowed)

New type #3: Choice

- New type: `choice{T;S;}`
- A value of this type is either a value of type `T` or a value of type `S`, example:

```
choice{string; Button; int;} u = “hello”;
u = new Button();
u = 42;
```

New type #4: Content class

- Like a normal class, except it contains a single unnamed member
- Useful for XML fidelity

```
public class book {
  struct{
    string title;
    choice{struct{editor editor;}*;
           struct{author author;}*;
    }
    string publisher;
    decimal price;
  }
}
```

XML Literals

- Now we have the types, we can write (strongly typed) XML literals in our code:

```
<!ELEMENT bib  (book*)>
<!ELEMENT book (title,
         (author* | editor*),
publisher, price)>
<!ELEMENT title (#PCDATA)>
<!ELEMENT publisher (#PCDATA)>
<!ELEMENT price  (#PCDATA)>
```

```
public class bib
  { struct{ book book; }*; }
public class book
  { struct {string title;
            choice {
             struct { editor editor;}*;
             struct { author author;}*;}
            string publisher;
            decimal price;}
  }
```

```
bib = <bib>
       <book year="1994">
        <title>TCP/IP Illustrated</title>
        <author><last>Stevens</last>
               <first>W.</first>
        </author>
        <publisher>Addison-Wesley</publisher>
        <price> 65.95</price>
       </book>
       <book>
        <title>The Economics of Technology and
               Content for Digital TV</title>
        <editor><last>Gerbarg</last>
                <first>Darcy</first>
                <affiliation>CITI</affiliation>
        </editor>
        <publisher>Kluwer Academic</publisher>
        <price>129.95</price>
       </book>
      </bib>;
```

Generalized member access

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- A key programming feature of Cω
- Generalize member access (the ‘dot’ operator) from just objects to all the new datatypes
- Aim: Make the dot behave like the ‘/’ in XPath

The power is in the dot!

Generalized member access

- Sequence:

```
string* ss;
ss.ToUpper();
```

string*

- Anonymous struct:

```
struct{int i; string s; string s;} x;
x.i;
x.s;
```

int

string*

- Choice:

```
choice{string;Person;int;} y;
y.Length;
```

choice{int;Float;?

XQuery Use Case Three

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For each book in the bibliography, list the title and authors, grouped inside a “result” element

XQUERY

```
for $b in $bs/book
return
 <result>
   {$b/title}
   {$b/author}
 <result>
```

Cω

```
foreach (b in bs.book)
{
  yield return <result>
                {b.title}
                {b.author}
               </result>;
}
```

First class SQL

- Elements of SQL have been built in to the language

```
String conn = "  ...Initial Catalog=Northwind;  ";
Database DB = new Database(conn);
Console.WriteLine("Please enter a city: ");
string input = Console.ReadLine();

res = select *
        from DB.Customers
       where City==input ;

Console.WriteLine("Customers from: "+input);
res.{Console.WriteLine(it.ContactName +
                       " --- " +
                       it.Phone);};
```

- In fact, we can use this construct over both in-memory and external data!

Part II: Formalization

Strategy

- Adopt a Featherweight Approach™
  - Identify a core fragment (subset) of the language
  - Give type system
  - Give operational semantics (preferably single-step)
  - Prove type soundness results
- Actually things are a little more complicated here:
  - Identify a core language, FCw
    - Define type system
  - Identify an inner language, ICw
    - Define type system
    - Type-directed compilation: FCw → ICw
    - Define operational semantics
    - Prove type soundness

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Expression

e	$::=$	$b \mid i$	Literals
	$\mid$	$e \oplus e$	Built-in operators
	$\mid$	x	Variable
	$\mid$	`null`	Null
	$\mid$	$(\tau)e$	Cast
	$\mid$	e `is` τ	Dynamic typecheck
	$\mid$	e `was` κ	Static typecheck for choice values
	$\mid$	`new` $\tau(e)$	Object creation
	$\mid$	`new` $\{\overline{be}\}$	Anonymous struct creation
	$\mid$	$e.f$	Field access
	$\mid$	$e[i]$	Field access by position
	$\mid$	pe	Promotable expression

Promotable expression

pe	$::=$	$x = e$	Variable assignment
	$\mid$	$e.m(\overline{e})$	Method invocation
	$\mid$	$e.\{e\}$	Apply-to-all

Binding expression

be	$::=$	$f = e$	Named binding
	$\mid$	e	Unnamed binding

Statement

s	$::=$	`;`	Skip
	$\mid$	pe`;`	Promoted expression
	$\mid$	`if` (e) s `else` s	Conditional
	$\mid$	$\tau\ x = e$`;`	Variable declaration
	$\mid$	`return` e`;`	Return statement
	$\mid$	`return;`	Empty return
	$\mid$	`yield return` e`;`	Yield statement
	$\mid$	`yield break;`	End of stream
	$\mid$	`foreach` $(\sigma\ x$ `in` $e)$ s	Foreach loop
	$\mid$	`while` (e) s	While loop
	$\mid$	$\{\overline{s}\}$	Block

See…it all fits on a single slide ☺

Operational semantics

- Transition relation of form:

$$(H, R), e \longrightarrow (H', R'), e'$$

- For expressions, pretty standard
- For statements, a little more tricky…

Semantics of foreach

- [Moving to C# 2.0] Tricky! For example:

```
foreach (T x in e) s
```

- is actually expanded to:

```
IEnumerator<T> enumerator =
((IEnumerable<T>)(e)).GetEnumerator();
try {
      while (enumerator.MoveNext()) {
            T x = (T)enumerator.Current;
            s;
      }
}
finally {
      enumerator.Dispose();
}
```

Iterator blocks

```
static IEnumerable<int> FromTo(int from, int to) {
	while (from <= to) yield return from++;
}
```

- gets rewritten to:

```
static IEnumerable<int> FromTo(int from, int to) {
	return new __Enumerable1(from, to);
}
```

- with **`GetEnumerator`** method:

```
public IEnumerator<int> GetEnumerator() {
	__Enumerable1 result = this;
	if (Interlocked.CompareExchange(ref __state, 1, 0) != 0)
	{	result = new __Enumerable1(__from, to);
		result.__state = 1;
	}
	result.from = result.__from;
	return result;
}
```

GetEnumerator

- From C# 2.0 documentation:

"The **first** time the **`GetEnumerator`** method is invoked, the enumerable **object itself** is returned. **Subsequent** invocations of the enumerable object's **`GetEnumerator`**, if any, return a **copy** of the enumerable object. Thus, each returned enumerator has its own state and changes in one enumerator will not affect another. The **`Interlocked.CompareExchange`** method is used to ensure thread-safe operation."

Our rules

- We captured all this complication **and** flattening of nested streams in just 8 transition rules!

Could we improve?

[Post ECOOP submission]

- Three criticisms of these semantics:
  1. Complicated!
  2. Trying to model too much? (In-place updating of stream closure)
  3. Don't see that nice co-routine behaviour

Gavin's latest cool rules

1. Move to a frame-stack semantics, à la Felleisen, GMB/Parkinson/Pitts (Middleweight Java), and others

(H, VS, code, FS)

FS = Frame stack
= Composition of frames
= current evaluation context
= future continuation!

2. Drop the in-place updating
   - Do everything by copying (it's just a spec. after all!)

Yield a value

[E-YieldV] $\langle H, MS \circ (MS' \circ VS), \texttt{yield return}(\sigma, v);, FS \circ \mathsf{Foreach}(\sigma', x, r, s) \circ FS' \rangle$
$\rightsquigarrow \langle H', MS'' \circ VS, s, \mathsf{Foreach}(\sigma', x, r', s) \circ FS' \rangle$

$$\begin{aligned}
\text{where } & \mathsf{Foreach} \notin FS \\
& H(r) = (\tau, -) \\
& r' \notin \mathrm{dom}(H) \\
& H' \stackrel{\text{def}}{=} H[r' \mapsto (\tau, [MS, FS])] \\
& MS'' \stackrel{\text{def}}{=} MS'[x \mapsto v]
\end{aligned}$$

Stream evaluation rules (in total)

[E-Foreach] $\langle H,\ VS, \texttt{foreach}\ (\sigma\ x\ \texttt{in}\ r)\ s',\ FS\rangle$
$\rightsquigarrow \langle H, MS \circ VS, \overline{s}, \mathsf{Foreach}(\sigma, x, r, s') \circ FS\rangle$ where $H(r) = (-, [MS, \overline{s}])$

[E-ForeachNull] $\langle H,\ VS, \texttt{foreach}\ (\sigma\ x\ \texttt{in null})\ s',\ FS\rangle$
$\rightsquigarrow \langle H,\ VS,\ ;,\ FS\rangle$

[E-YieldV] $\langle H, MS \circ (MS' \circ VS), \texttt{yield return}(\sigma, v);, FS \circ \mathsf{Foreach}(\sigma', x, r, s) \circ FS'\rangle$
$\rightsquigarrow \langle H', MS'' \circ VS, s, \mathsf{Foreach}(\sigma', x, r', s) \circ FS'\rangle$ where $\mathsf{Foreach} \notin FS$
$H(r) = (\tau, -)$
$r' \notin \mathrm{dom}(H)$
$H' \stackrel{\mathrm{def}}{=} H[r' \mapsto (\tau, [MS, FS])]$
$MS'' \stackrel{\mathrm{def}}{=} MS'[x \mapsto v]$

[E-YieldBr] $\langle H, MS \circ VS, \texttt{yield break};, FS \circ \mathsf{Foreach}(\sigma, x, r, s) \circ FS'\rangle$
$\rightsquigarrow \langle H,\ VS,\ ;,\ FS'\rangle$ where $\mathsf{Foreach} \notin FS$

[E-YieldNest] $\langle H, MS \circ VS, \texttt{yield return}(\sigma\texttt{*},v);, FS \circ \mathsf{Foreach}(\sigma', x, r, s) \circ FS'\rangle$
$\rightsquigarrow \langle H',\ VS, \texttt{foreach}(\sigma'\ \texttt{x in}\ v)\ s, \mathsf{Foreach}(\sigma', x, r', s) \circ FS'\rangle$ where $\mathsf{Foreach} \notin FS$
$H(r) = (\tau, -)$
$r' \notin \mathrm{dom}(H)$
$H' \stackrel{\mathrm{def}}{=} H[r' \mapsto (\tau, [MS, FS])]$

Type soundness

- We can prove that our operational semantics satisfy a type safety property

- Proved in “standard way”:
  - Subject reduction theorem
  - Progress theorem

Related work

- Building database programming languages:
  - Too much work to mention!
  - Lots of academic work, e.g. Galileo, Fibonacci, Tycoon, HaskellDB, …
  - Industrial work: SQLJ, …
- Integrating XML with programming languages:
  - CDuce (ENS/INRIA), Links (Edinburgh)
  - Xtatic (UPenn)
  - XJ (IBM Research)

Lots more work to do here!

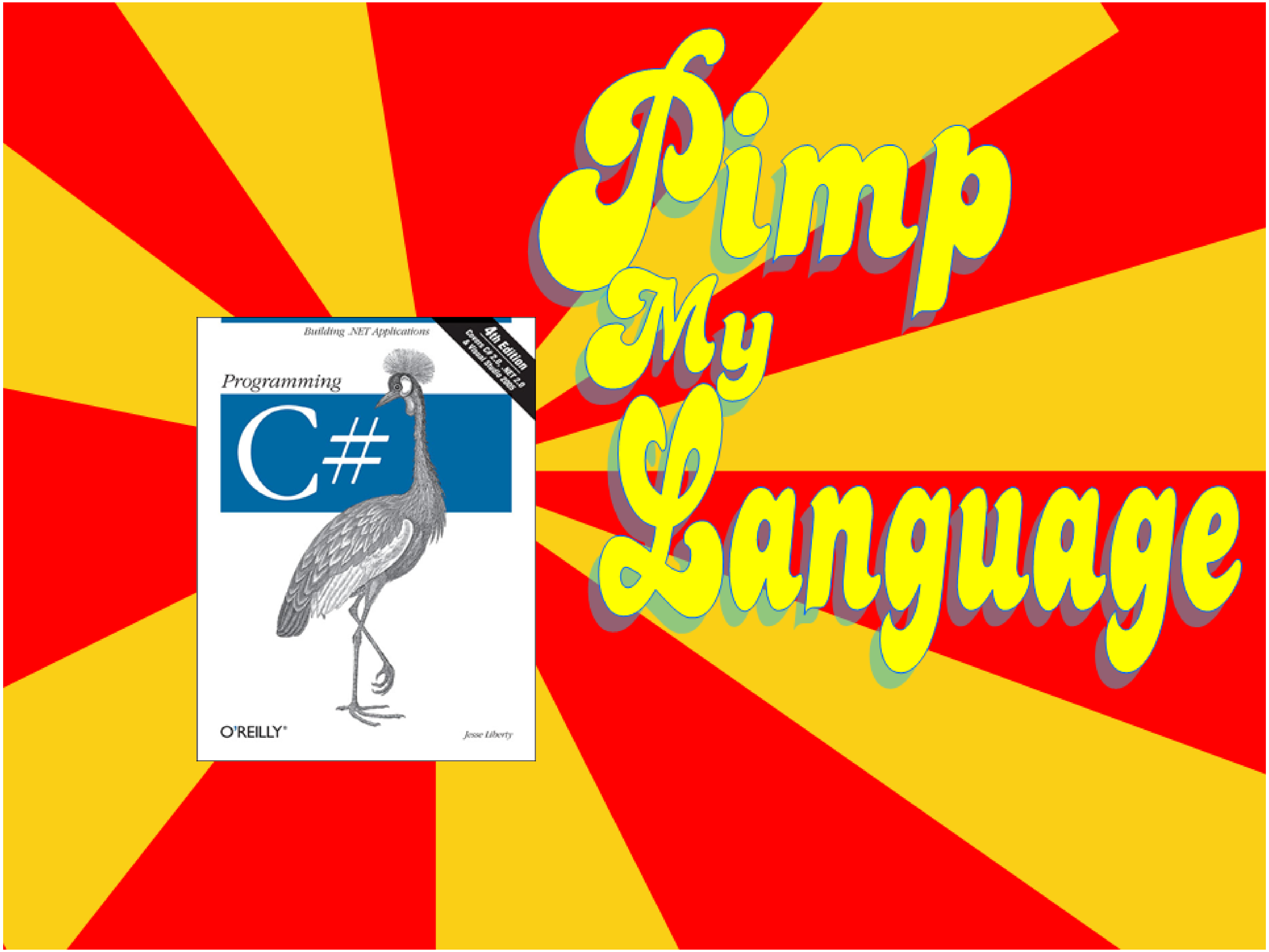
Summary

- We took (the entire) C# as our starting point
- We "grew" it with minimal extensions to allow
  - Relational/Semi-structured data manipulation/creation
  - Query-like constructs
  - (asynchronous concurrency primitives)
- We've proved it correct!
- Our hope: Cω is a language well-suited for data-intensive, distributed applications

- Compiler is freely available from:

  http://research.microsoft.com/comega

Another perspective…



Thank you! Any questions?

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