A Natural Programming Model for Distributed Computing

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My Research

- The systems and languages end of SE
  - language tools for distributed computing
    - NRMI, J-Orchestra, GOTECH
      *ICDCS’03, ECOOP’02, Middleware’04, ICSM’05, IEEE PervComp, ASE’03, ICSE’05, ...
    - automatic testing
      - JCrasher, Check-n-Crash (CnC), DSD-Crasher
        *Softw.Prac.&Exp., ICSE’05, ICSE’06 ER, ISSTA’06, ...
  - program generators and domain-specific languages
    - Meta-AspectJ (MAJ), SafeGen, JTS, DiSTiL
      *GPCE’04 (best paper), ICSE’06 ER, PEPM’04, GPCE’05, ICSR’98, ...
  - multiparadigm programming
    - FC++, LC++
      *ICFP’00, JFP, Softw.Prac.&Exp., ...
  - software components
    - mixin layers, layered libraries
      *ECOOP’98, ICSR’98, ICSR’02, TOSEM, ...
  - memory management
    - EELRU, compressed VM, trace reduction, adaptive replacement
      *SIGMETRICS’99 (2x), Usenix’99 (best paper), TOMACS, Usenix’00, ISMM’04, ...

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This Talk

- NRMI: a middleware facility that makes distributed systems programming easier
  - solves a long standing, well-known open problem!
Language Tools for Distributed Computing

- What does “language tools” mean?
  - middleware libraries, compiler-level tools, program generators, domain-specific languages
- What is a distributed system?
  - “A collection of independent computers that appears to users as a single, coherent system”
Why Language Tools for Distributed Computing?

- Why Distributed Computing?
  - networks changed the way computers are used
  - programming distributed systems is hard!
    - partial failure, different semantics (distinct memory spaces), high latency, natural multi-threading
  - are there simple programming models to make our life easier?
- “The future is distributed computation, but the language community has done very little to address that possibility.”
  
  Rob Pike—“Systems Software Research is Irrelevant”, 2000
A very common model is RPC middleware:
- hide network communication behind a procedure call ("remote procedure call")
- execute call on server, but make it look to client like a local call
  - only, not quite: need to be aware of different memory space
- Our problem: make remote calls more like local calls!
Common RPC Programming Model \textit{(call semantics)}: Call-by-copy

- To call a remote procedure, copy argument-reachable data to server site, return value back
  - data packaged and sent over net (“pickling”, “serialization”)

```
int sum(Tree tree) {...}
```

```
t
```

```
9
7
1
3
```

```
4
9
7
1
3
```

```
4
9
7
1
3
```

```
Network
```

```
Client site
```

```
Server site
```

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Other Calling Semantics: Call-by-Copy-Restore

- Call-by-copy (call-by-value) works fine when the remote procedure does not need to modify arguments
  - otherwise, changes not visible to caller, unlike local calls
  - in general, not easy to change shared state with non-shared address spaces

- Call-by-copy-restore is a common idea in distributed systems (and in some languages, as call-by-value-result):
  - copy arguments to remote procedure, copy results of execution back, restore them in original variables
  - resembles call-by-reference on a single address space
Copy-Restore Example

void swap(Obj a, Obj b) {...}

swap(n, m);

Network
A Long Standing Challenge

- Works ok for single variables, but not complex data!
- The distributed systems community has long tried to define call-by-copy-restore as a general model, for all data
- A textbook problem for over 15 years:
  - “... Although call-by-copy-restore can handle pointers to simple array structures, we still cannot handle the most general case of a pointer to an arbitrary data structure, such as a complex graph.”
  - Tanenbaum and Steen, Distributed Systems, Prentice Hall
- The DCE RPC design tried to solve it but did not
Our Contribution: NRMI

- The NRMI ("Natural RMI") middleware facility solves the general problem *efficiently*
  - a drop-in replacement of Java RMI, also supporting full call-by-copy-restore semantics
  - *invariant: all changes from the server are visible to client when RPC returns*
    - no matter what data are used and how they are linked
    - this is the hallmark property of copy-restore

- The difficulty:
  - having pointers means having *aliasing*: multiple ways to reach the same object—need to correctly update all
Solution Idea (by example)

- Consider what changes a procedure can make

```java
void foo(Tree tree) {
    tree.left.data = 0;
    tree.right.data = 9;
    tree.right.right.data = 8;
    tree.left = null;
    Tree temp =
        new Tree(2, tree.right.right, null);
    tree.right.right = null;
    tree.right = temp;
}
```
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Previous Attempts: DCE RPC

- DCE RPC is the foremost example of a middleware design that supports restoring remote changes.
- The most widespread DCE RPC implementation is Microsoft RPC (the base of middleware for the Microsoft operating systems).
- Supports “full pointers” (ptr) which can be aliased.
- No true copy-restore: aliases not correctly updated.
  - for complex structures, it’s not enough to copy back and restore the value of arguments.
DCE RPC: stops short!

Network

alias1

alias2

Client site

Server site

Completely inconsistent!
Solution Idea (by example)

- Key insight: the changes we care about are all changes to objects reachable from objects that were originally reachable from arguments to the call.

- Three critical cases:
  - Changes may be made to data now unreachable from t, but reachable through other aliases.
  - New objects may be created and linked.
  - Modified data may now be reachable only through new objects.
NRMI Algorithm (by example): identify all reachable

Client site

Server site

Network
Algorithm (by example): execute remote procedure

Client site

Server site

Network
Algorithm (by example): send back all reachable
Algorithm (by example): match reachable maps
Algorithm (by example): update original objects
Algorithm (by example): adjust links out of original objects

Network

Client site
Algorithm (by example): adjust links out of new objects

Client site
Algorithm (by example): garbage collect

Client site
Usability and Performance

- NRMI makes programming easier
  - no need to even know aliases
  - even if all known, eliminates many lines of code (~50 per remote call/argument type—26% or more of the program for our benchmarks)
- common scenarios:
  - GUI patterns like MVC: many views alias same model
  - multiple indexing (e.g., customers + transactions crossreferenced)
- We have a highly optimized implementation
  - algorithm implemented by tapping into existing serialization mechanism, optimized with Java 1.4+ “unsafe” facility for direct memory access
Experimental Results

Tree of 256 nodes

- Bench1
- Bench2
- Bench3

- NRMI
- Java RMI + extra code
- Java RMI, remote ref. (no extra code)

Time in ms
Retrospective: What Helped Solve the Problem?

- An instance of “looking at things from the right angle”
  - a languages background helped a lot:
    - with defining precisely what copy-restore means
    - with identifying the key insight
    - with coming up with an efficient algorithm

```plaintext
server does not generate requests to the client. (This would be dramatically less efficient than our approach, as our measurements show.) We do not “generate special code in the server” for using pointers: the server code can proceed at full speed—not even the overhead of a local read or write barrier is necessary.

We implemented our ideas in the form of NRMI (Nat-
```
Expert Testimony

• “I found your paper quite interesting...there are some clever things that you have done, and for the kinds of applications you are talking about, I think NRMI would be quite useful.”

  Jim Waldo (via email)
  [first ORB, Java RMI, Jini]
Summary: This Talk

- NRMI: a middleware facility that makes distributed systems programming easier
  - solves a long standing, well-known open problem!
Higher-level Distributed Programming Facilities

- NRMI is a medium-level facility: it gives the programmer full control, imposes requirements
  - good for performance and flexibility
  - low automation
- For single-threaded clients and stateless servers, NRMI semantics is (provably) identical to local procedure calls
  - but statelessness is restrictive
- There are higher-level models for programming distributed systems
  - the higher the level, the more automation
  - the higher the level, the smaller the domain of applicability
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Thank you!
Questions?