Distributed Computing with Oz/Mozart (VRH 11)

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Overview

- Designing a platform for robust distributed programming requires thinking about both language design and distributed algorithms
  - Distribution and state do not mix well (global coherence); the language should help (weaker forms of state, different levels of coherence)
- We present one example design, the Mozart Programming System
  - Mozart implements efficient network-transparent distribution of the Oz language, refining language semantics with distribution
- We give an overview of the language design and of the distributed algorithms used in the implementation
  - It is the combination of the two that makes distributed programming simple in Mozart
- Ongoing work
  - Distribution subsystem (DSS): factor distribution out of emulator
  - Service architecture based on structured overlay (P2PS and P2PKit)
  - Self management by combining structured overlay and components
  - Capability based security

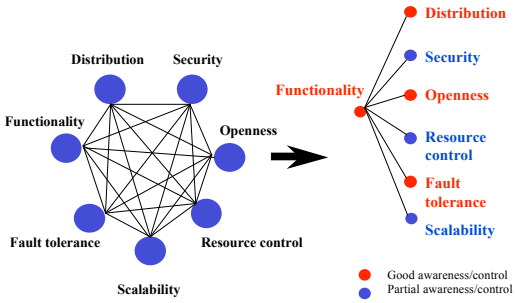
Mozart research at a glance

- Oz language
  - A concurrent, compositional, object-oriented language that is state-aware and has dataflow synchronization
  - Combines simple formal semantics and efficient implementation
- Strengths
  - Concurrency: ultralightweight threads, dataflow
  - Distribution: network transparent, network aware, open
  - Inferencing: constraint, logic, and symbolic programming
  - Flexibility: dynamic, no limits, first-class compiler
- Mozart system
  - Development since 1991 (distribution since 1995), 10-20 people for >10 years
  - Organization: Mozart Consortium (until 2005, three labs), now Mozart Board (we invite new developers!)
  - Releases for many Unix/Windows flavors; free software (X11-style open source license); maintenance; user group; technical support (http://www.mozart-oz.org)
- Research and applications
  - Research in distribution, fault tolerance, resource management, constraint programming, language design and implementation
  - Applications in multi-agent systems, "symbol crunching", collaborative work, discrete optimization (e.g., tournament planning)

Basic principles

- *Refine* language semantics with a distributed semantics
  - Separates functionality from distribution structure (network behavior, resource localization)
- Three properties are crucial:
  - Transparency
    - Language semantics identical independent of distributed setting
    - Controversial, but let's see how far we can push it, *if* we can also think about language issues
  - Awareness
    - Well-defined distribution behavior for each language entity: simple and predictable
  - Control
    - Choose different distribution behaviors for each language entity
    - Example: objects can be stationary, cached (mobile), asynchronous, or invalidation-based, with same language semantics

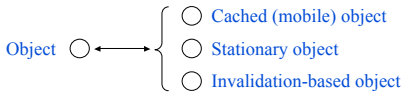
Mozart today



Language design

- Language has a layered structure with three layers:
  - Strict functional core (stateless): exploit the power of lexically scoped closures
  - Single-assignment extension (dataflow variables + concurrency + laziness): provides the power of concurrency in a simple way ("declarative concurrency")
  - State extension (mutable pointers / communication channels): provides the advantages of state for modularity (object-oriented programming, many-to-one communication and active objects, transactions)
- Dataflow extension is well-integrated with state: to a first approximation, it can be ignored by the programmer (it is not observable whether a thread temporarily blocks while waiting for a variable's value to arrive)
- Layered structure is well-adapted for distributed programming
  - This was a serendipitous discovery that led to the work on distributing Oz
- Layered structure is not new: see, e.g., Smalltalk (blocks), Erlang (active objects with functional core), pH (Haskell + I-structures + M-structures), Java (support for immutable objects), SALSA (actors with object-oriented core)

Adding distribution



- Each language entity is implemented with one or more distributed algorithms. The choice of distributed algorithm allows tuning of network performance.
- Simple programmer interface: there is just one basic operation, passing a language reference from one process (called "site") to another. This conceptually causes the processes to form one large store.
- How do we pass a language reference? We provide an ASCII representation of language references, which allows passing references through any medium that accepts ASCII (Web, email, files, phone conversations, …)
- How do we do fault tolerance? We will see later…

Example: sharing an object (1)

```
class Coder
  attr seed
  meth init(S) seed:=S end
  meth get(X)
    X=@seed
    seed:=(@seed*23+49) mod 1001
  end
end

C={New Coder init(100)}

T={Connection.offer C}
```

- Define a simple random number class, Coder
- Create one instance, C
- Create a ticket for the instance, T
- The ticket is an ASCII representation of the object reference

Example: sharing an object (2)

```
C2={Connection.take T}

local X in
   % invoke the object
   {C2 get(X)}
   % Do calculation with X
   ...
end
```

- Let us use the object C on a second site
- The second site gets the value of the ticket T (through the Web or a file, etc.)
- We convert T back to an object reference, C2
- C2 and C are references to the same object

What distributed algorithm is used to implement the object?

Example: sharing an object (3)

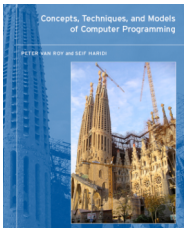
- C and C2 are the **same object**: there is a distributed algorithm guaranteeing coherence
- Many distributed algorithms are possible, as long as the language semantics are respected
- By default, Mozart uses a ***cached object***: the object state synchronously moves to the invoking site. This makes the semantics easy, since all object execution is local (e.g., exceptions raised in local threads). A cached object is a kind of mobile object.
- Other possibilities are a stationary object (behaves like a server, similar to RMI), an invalidation-based object, etc.

Example: sharing an object (4)

- Cached objects:
  - The object state is mobile; to be precise, the *right to update the object state* is mobile, moving synchronously to the invoking site
  - The object class is stateless (a record with method definitions, which are procedures); it therefore has its own distributed algorithm: it is copied once to each process referencing the object
  - We will see the protocol of cached objects later. The mobility of a cached object is lightweight (maximum of three messages for each move).

More examples

- Many more programming examples are given in chapter 11 of the book "Concepts, Techniques, and Models of Computer Programming" (a.k.a. CTM)
- There are examples to illustrate client/servers, distributed lexical scoping, distributed resource management, open computing, and fault tolerance
- We will focus on cached objects



Language entities and their distribution protocols

- Stateless (records, closures, classes, software components)
  - Coherence assured by copying (eager immediate, eager, lazy)
- Single-assignment (dataflow variables, streams)
  - Allows to decouple communications from object programming
  - To first approximation: they can be completely ignored by the programmer (things work well with dataflow variables)
  - Uses distributed binding algorithm (in between stateless and stateful!)
- Stateful (objects, communication channels, component instances)
  - Synchronous: stationary protocol, cached (mobile) protocol, invalidation protocols
  - Asynchronous FIFO: channels, asynchronous object calls

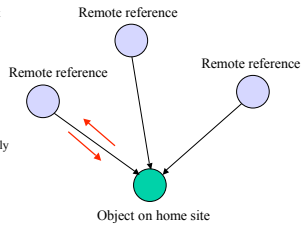
Distributed object-oriented programming

Paths to distributed object-oriented programming

- Simplest case
  - **Stationary object**: synchronous, similar to Java RMI but fully transparent, e.g., automatic conversion local↔ distributed
- Tune distribution behavior ***without changing language semantics***
  - Use different distributed algorithms depending on usage patterns, but language semantics unchanged
  - **Cached (« mobile ») object**: synchronous, moved to requesting site before each operation → for shared objects in collaborative applications
  - **Invalidation-based object**: synchronous, requires invalidation phase → for shared objects that are mostly read
- Tune distribution behavior ***with possible changes to language semantics***
  - Sometimes changes are unavoidable, e.g., to overcome large network latencies or to do replication-based fault tolerance (more than just fault detection)
  - **Asynchronous stationary object**: send messages to it without waiting for reply; synchronize on reply or remote exception
  - **Transactional object**: set of objects in a « transactional store », allows local changes without waiting for network (optimistic or pessimistic strategies)

Stationary object

- Each object invocation sends a message to the object and waits for a reply (2 network hops)
- Creation syntax in Mozart:
  - Obj = {NewStat Cls Init}
- Concurrent object invocations stay concurrent at home site (home process)
- Exceptions are correctly passed back to invoking site (invoking process)
- Object references in messages automatically become remote references

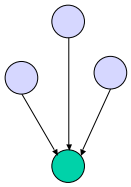


Comparison with Java RMI

- Lack of transparency
  - Java with RMI is only network transparent when parameters and return values are stateless objects (i.e., immutable) or remote objects themselves
    - otherwise changed semantics
  - Consequences
    - difficult to take a multi-threaded centralized application and distribute it.
    - difficult to take a distributed application and change distribution structure.
- Control
  - Compile-time decision (to distribute object)
  - Overhead on RMI to same machine
  - Object always stationary (for certain kinds of application - severe performance penalty)
- Ongoing work in Java Community
  - RMI semantics even on local machine
  - To fix other transparency deficiencies in RMI

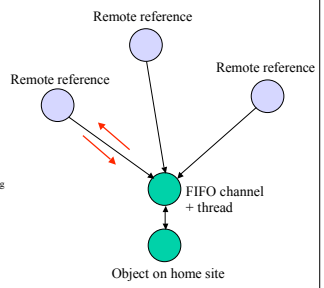
Notation for the distributed protocols

- We will use a graph notation to describe the distributed protocols. Protocol behavior is defined by message passing between graph nodes and by graph transformations.
- Each language entity (record, closure, dataflow variable, thread, mutable state pointer) is represented by a node
- Distributed language entities are represented by two additional nodes, proxy and manager. The proxy is the local reference of a remote entity. The manager coordinates the distributed protocol in a way that depends on the language entity.
- For the protocols shown, authors have proven that the distributed protocol correctly implements the language semantics (see publications)



« Active » object

- Variant of stationary object where the home object always executes in one thread
- Concurrent object invocations are sequentialized
- Use is transparent: instead of creating with NewStat, create with NewActive:
  - Obj = {NewActiveSync Class Init}
  - Obj = {NewActiveAsync Class Init}
- Execution can be synchronous or asynchronous
  - In asynchronous case, any exception is swallowed; see later for correct error handling

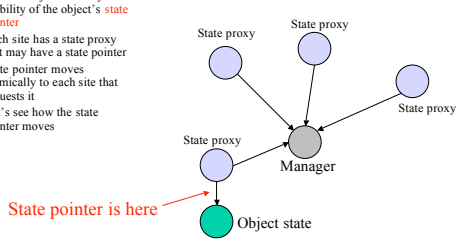


Cached (« mobile ») object (1)

- For collaborative applications, e.g., graphical editor, stationary objects are not good enough.
- Performance suffers with the obligatory round-trip message latency
- A cached object moves to each site that uses it
  - A simple distributed algorithm (token passing) implements the atomic moves of the object state
  - The object class is copied on a site when object is first used; it does not need to be copied subsequently
  - The algorithm was formalized and extended and proved correct also in the case of partial failure

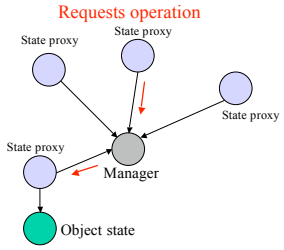
Cached (« mobile ») object (2)

- Heart of object mobility is the mobility of the object's state pointer
- Each site has a state proxy that may have a state pointer
- State pointer moves atomically to each site that requests it
- Let's see how the state pointer moves



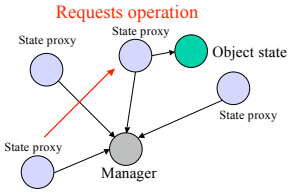
Cached (« mobile ») object (3)

- Another site requests an object operation
- It sends a message to the manager, which serializes all such requests
- The manager sends a forwarding request to the site that currently has the state pointer



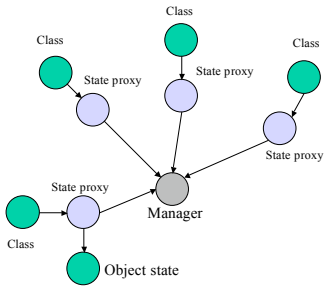
Cached (« mobile ») object (4)

- Finally, the requestor receives the object state pointer
- All subsequent execution is local on that site (no more network operations)
- Concurrent requests for the state are sent to the manager, etc., which serializes them



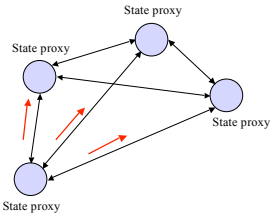
Cached (« mobile ») object (5)

- Let's look at the complete object
- The complete object has a class as well as an internal state
- A class is a value
  - To be precise, it is a constant: it does not change
- Classes do not move; they are copied to each site upon first use of the object there



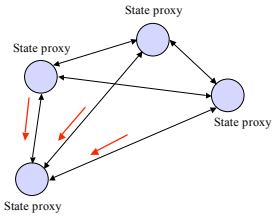
Invalidation-based object (1)

- An invalidation-based object is optimized for the case when object reads are needed frequently and object writes are rare (e.g., virtual world updates)
- A state update operation is done in two phases:
  - Send an update to all sites
  - Receive acknowledgement from all sites
- Object invocation latency is 2 network hops, but depends on the slowest site



Invalidation-based object (2)

- A new site that wants to broadcast has first to invalidate the previous broadcaster
- If several sites want to broadcast concurrently, then there will be long waits for some of them



Transactional object

- Only makes sense for a set of objects (call it a « transactional store »), not for a single object
- Does both latency tolerance and fault tolerance
  - Separates distribution & fault tolerance concerns: the programmer sees a single set of objects with a transactional interface
- Transactions are atomic actions on sets of objects. They can commit or abort.
  - Possibility of abort requires handling speculative execution, i.e., care is needed to interface between a transactional store and its environment
- In Mozart, the GlobalStore library provides such a transactional store
  - Authors are working on reimplementing it using peer-to-peer

Asynchronous FIFO stationary object

- Synchronous object invocations are limited in performance by the network latency
  - Each object invocation has to wait for at least a round-trip before the next invocation
- To improve performance, it would be nice to be able to invoke an object asynchronously, i.e., without waiting for the result
  - Invocations from the same thread done in same order (FIFO)
  - But this will still change the way we program with objects
- How can we make this as transparent as possible, i.e., change as little as possible how we program with objects?
  - Requires new language concept: dataflow variable
  - In many cases, network performance can be improved with little or no changes to an existing program

Dataflow concurrency in distributed computing

- Dataflow concurrency is an important form of concurrent programming that is much simpler than shared-state concurrency [see VRH 4]
- Oz supports dataflow concurrency by making stateless programming the default and by making threads very lightweight
- Support for dataflow concurrency is important for distributed programming
  - For example, asynchronous programming is easy
- In both centralized and distributed settings, dataflow concurrency is supported by dataflow variables
  - A single-assignment variable similar to a logic variable

Dataflow variables (1)

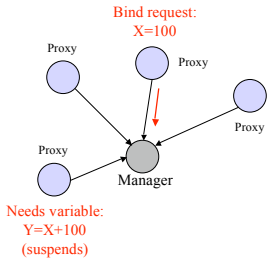
- A dataflow variable is a single-assignment variable that can be in one of two states, unbound (the initial state) or bound (it has its value)
- Dataflow variables can be created and passed around (e.g., in object messages) before being bound
- Use of a dataflow variable is transparent: it can be used as if it were the value!
  - If the value is not yet available when it is needed, then the thread that needs it will simply suspend until the value arrives
  - This is transparent to the programmer
  - Example:

```
thread X=100 end          Y=X+100
(binds X)                 (uses X)
```

- A distributed protocol is used to implement this behavior in a distributed setting

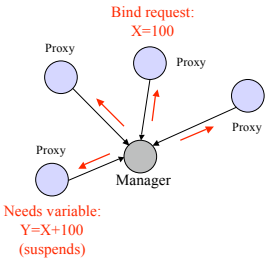
Dataflow variables (2)

- Each dataflow variable has a distributed structure with proxy nodes and a manager node
- Each site that references the variable has a proxy to the manager
- The manager accepts the first bind request and forwards the result to the other sites
- Dataflow variables passed to other sites are automatically registered with the manager
- Execution is order-independent: same result whether bind or need comes first



Dataflow variables (3)

- When a site receives the binding, it wakes up any suspended threads
- If the binding arrives before the thread needs it, then there is no suspension



Dataflow variables (4)

- The real protocol is slightly more complex than this
- What happens when there are two binding attempts: if second attempt is erroneous (conflicting bindings), then an exception is raised on the guilty site
  - What happens with value-value binding and variable-variable binding: bindings are done correctly
  - Technically, the operation is called distributed rational tree unification [see ACM TOPLAS 1999]
- Optimization for stream communication
  - If bound value itself contains variables, they are registered before being sent
  - This allows asynchronous stream communication (no waiting for registration messages)

Dataflow variable and object invocation (1)

- Similar to an active object
  - Return values are passed with dataflow variables:

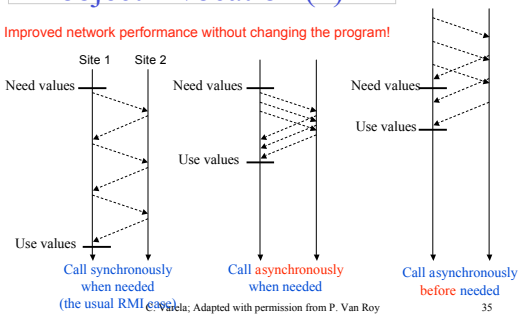
    C={NewAsync Cls Init}
    (create on site 1)

    {C get(X1)}
    {C get(X2)}
    {C get(X3)}
    X=X1+X2+X3
    (call from site 2)

- Can synchronize on error
  - Exception raised by object:
    {C get(X1) E}
    (synchronize on E)
  - Error due to system fault (crash or network problem):
    - Attempt to use return variable (X1 or E) will signal error (lazy detection)
    - Eager detection also possible

Dataflow variable and object invocation (2)

Improved network performance without changing the program!



Fault tolerance

- **Reflective failure detection**
  - Reflected into the language, at level of single language entities
  - Two kinds: permanent process failure and temporary network failure
  - Both synchronous and asynchronous detection
    - Synchronous: exception when attempting language operation
    - Asynchronous: language operation blocks; user-defined operation started in new thread
    - Authors' experience: asynchronous is better for building abstractions
- Building fault-tolerant abstractions
  - Using reflective failure detection we can build abstractions in Oz
  - Example: *transactional store*
    - Set of objects, replicated and accessed by transactions
    - Provides both fault tolerance and network delay compensation
    - Lightweight: no persistence, no dependence on file system

Distributed garbage collection

- The centralized system provides automatic memory management with a garbage collector (dual-space copying algorithm)
- This is extended for the distributed setting:
  - First extension: weighted reference counting. Provides fast and scalable garbage collection if there are no failures.
  - Second extension: time-lease mechanism. Ensures that garbage will eventually be collected even if there are failures.
- These algorithms do not collect distributed stateful cycles, i.e., reference cycles that contain at least two stateful entities on different processes
  - All known algorithms for collecting these are complex and need global synchronization: they are impractical!
  - So far, we find that programmer assistance is sufficient (e.g., dropping references from a server to a no-longer-connected client). This may change in the future as we write more extensive distributed applications.

Implementation status

- All described protocols are fully implemented and publicly released in the Mozart version 1.3.1
  - Including stationary, cached mobile, and asynchronous object
  - Including dataflow variables with distributed rational tree unification
  - Including distributed garbage collection with weighted reference counting and time-lease
  - Except for the invalidation-based object, which is not yet implemented
  - Transactional object store was implemented but is no longer supported (GlobalStore) – will be superceded by peer-to-peer
- Current work
  - General distribution subsystem (DSS)
  - Structured overlay network (peer-to-peer) and service architecture (P2PS, P2PKit)

Exercises

1. Cached (mobile) objects performance depends on pattern of distributed object usage. Write a program that exhibits good performance given the cached object protocol, and write a program that exhibits bad performance. Hint: Use a pattern of object invocations that would require the object's state (potentially large) to be moved back and forth between multiple machines.
2. Determine differences between Oz active objects with asynchronous calls and actors.
3. How would you implement the "invalidation-based" protocol in an actor language?