Robust distributed programming in the Mozart platform: the importance of language design and distributed algorithms

La programmation répartie robuste dans la plate-forme Mozart : le rôle du langage et de l'algorithmique répartie

Langages et Modèles à Objets (LMO'2002)

Peter Van Roy
Département d'Ingénierie Informatique
Université catholique de Louvain
25 janvier 2002

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, 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
- Conclusions and ongoing work
  - Projects starting in high availability, security, peer-to-peer

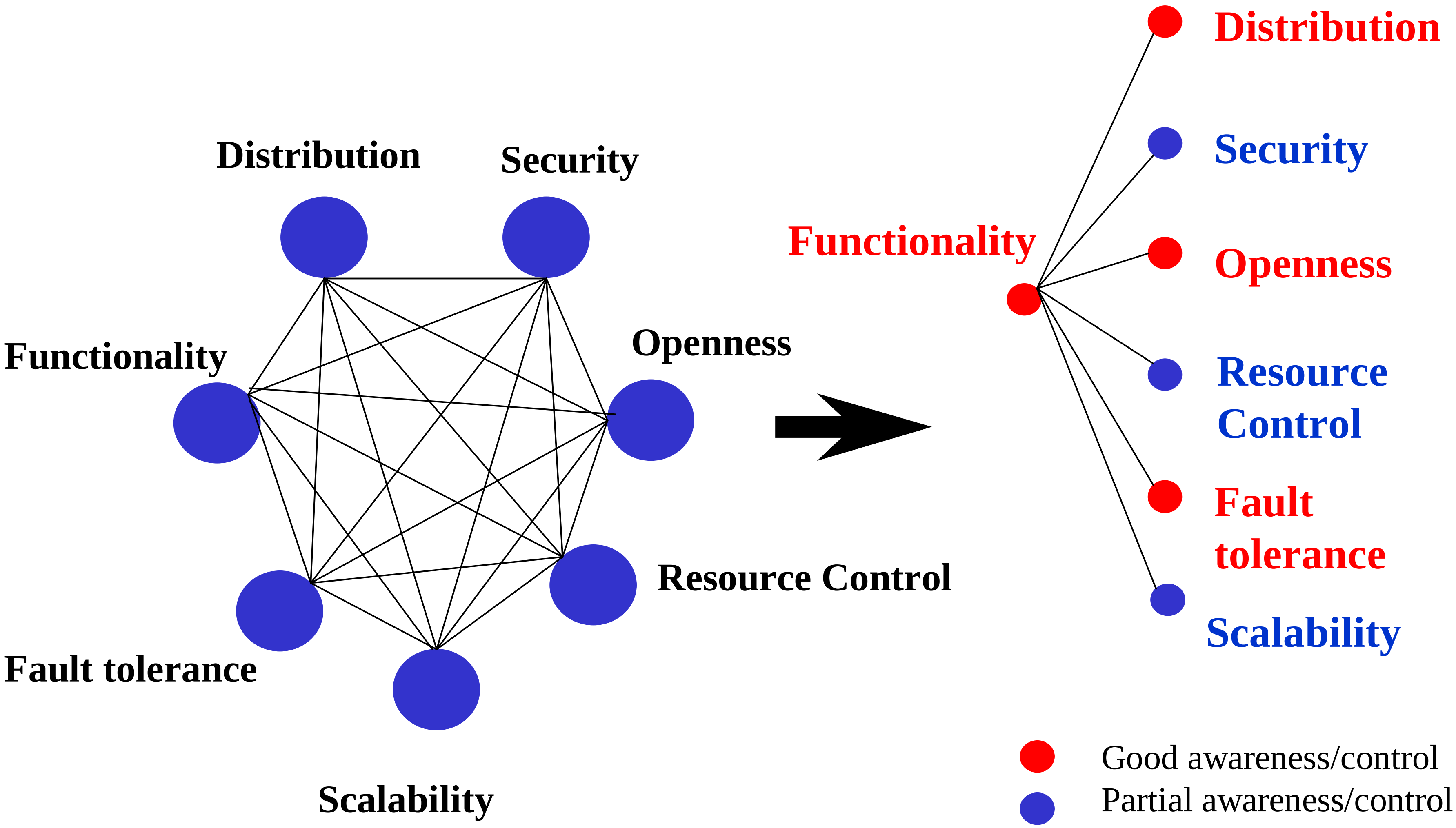
Mozart at a Glance

- Oz Language
  - A concurrent, compositional, object-oriented language that is state-aware and has dataflow synchronization
  - 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
  - Under development since 1991 (distribution since 1995), 10-20 people for 10 years
  - Mozart Consortium: Universität des Saarlandes (Germany), Swedish Institute of Computer Science (Sweden), Université catholique de Louvain (Belgium)
  - 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 managements, 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
    - Can give different distribution behaviors for a given language entity
    - Example: objects are stationary, cached (mobile), asynchronous, or invalidation-based, with same language semantics

Mozart today

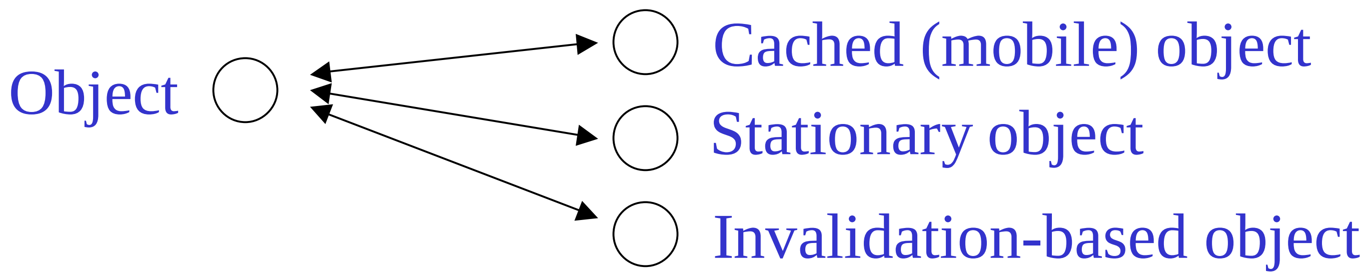


Language design

- Language has a layered structure with three layers:
  - Strict functional core (stateless): exploit the power of lexically-scoped closures (“call backs done right”)
  - 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), even Java (support for immutable objects)

See book: http://www.info.ucl.ac.be/people/PVR/book.html

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 in the talk…

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 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), 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); 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 in the talk, together with its fault behavior. The mobility of a cached object is lightweight (maximum of three messages for each move).

Language entities and their distribution protocols

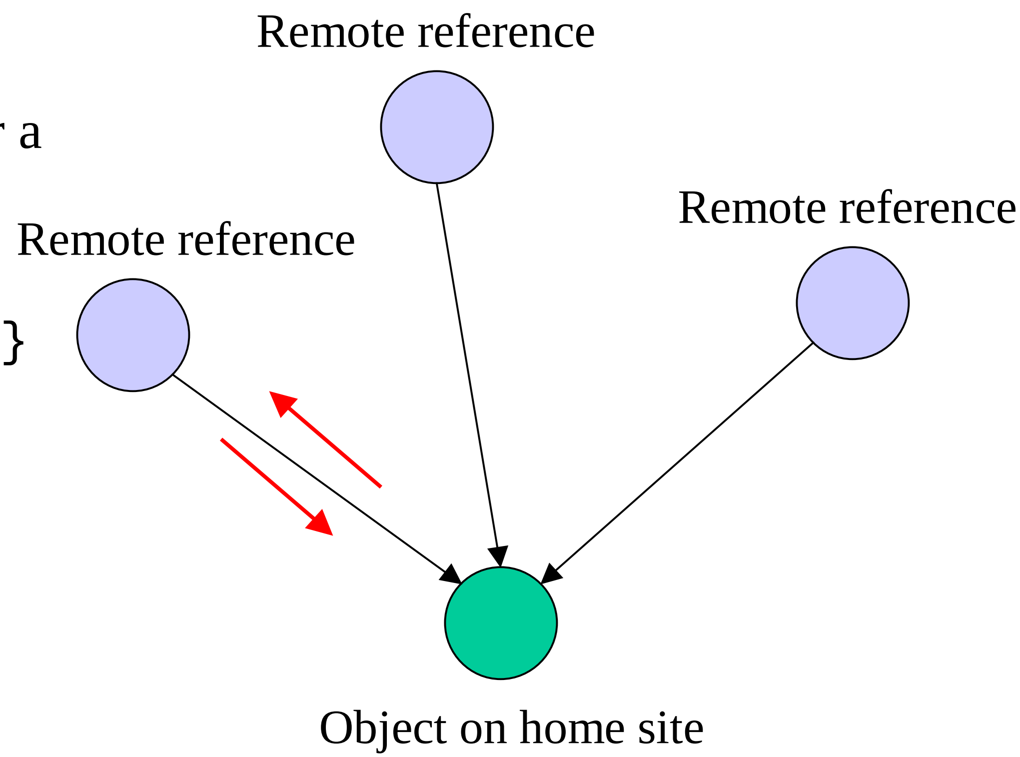
- Stateless (records, closures, classes, software components)
  - Coherence assured by copying (eager immediate, eager, lazy)
- Single-assignment (dataflow variables)
  - Allows to decouple communications from object programming
  - To first approximation: can be completely ignored
  - Uses distributed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

The path to true distributed object-oriented programming

- Simplest case
  - **Stationary object**: synchronous, similar to Java RMI but fully transparent, i.e., 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
- Exceptions are correctly passed back to invoking site
- Object references in messages automatically become remote references

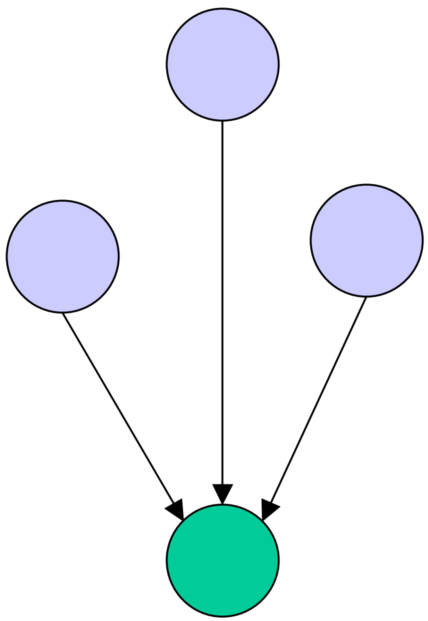


Comparison with Java RMI

- 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
  - Consequence
    - difficult to take a multi-threaded centralized application and distribute it.
    - difficult to take a distributed application and to change the 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
  - Java Enterprise beans within a cluster

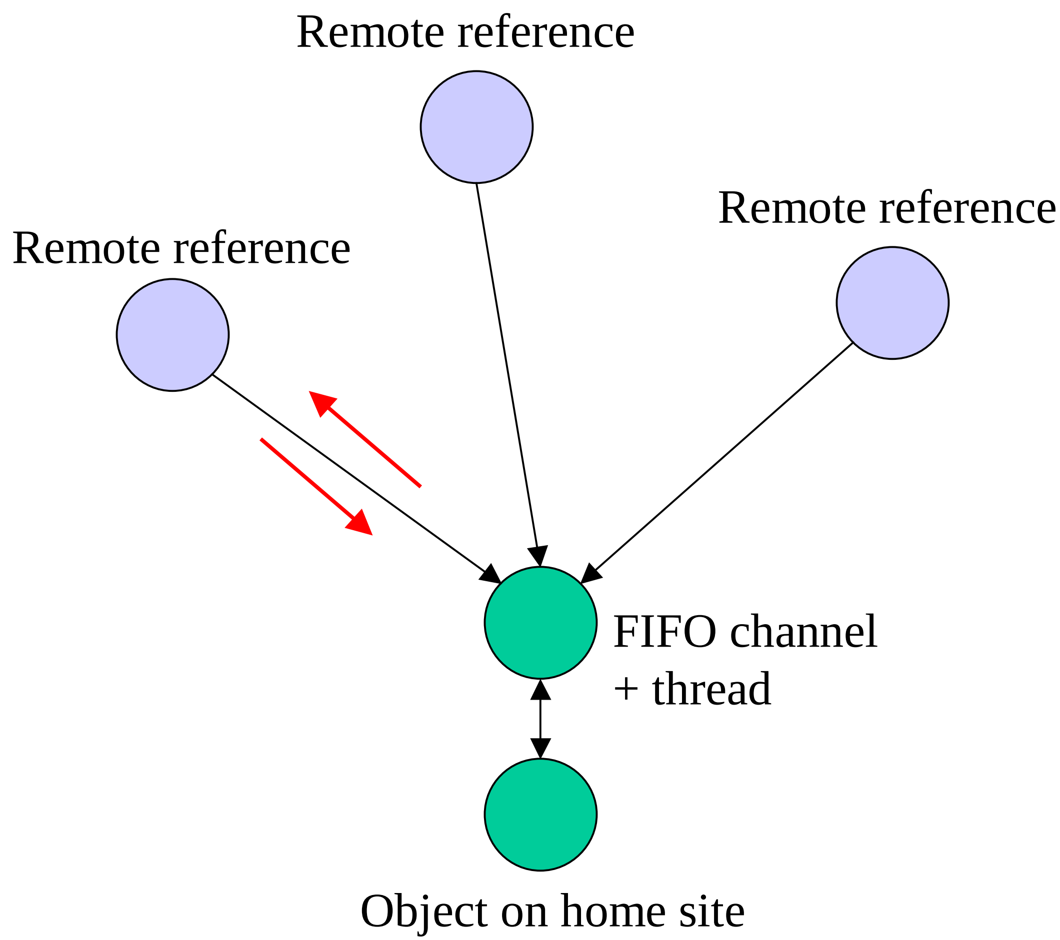
Notation for the distributed protocols

- We will use a graph notation to describe the distributed protocols.
- Each language entity (record, closure, dataflow variable, thread, mutable state pointer, class) 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 we will show, we 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 Cls Init}`
  - `Obj = {NewActiveAsync Cls Init}`
- Execution can be synchronous or asynchronous
  - In asynchronous case, any exception is swallowed; see later for correct error handling

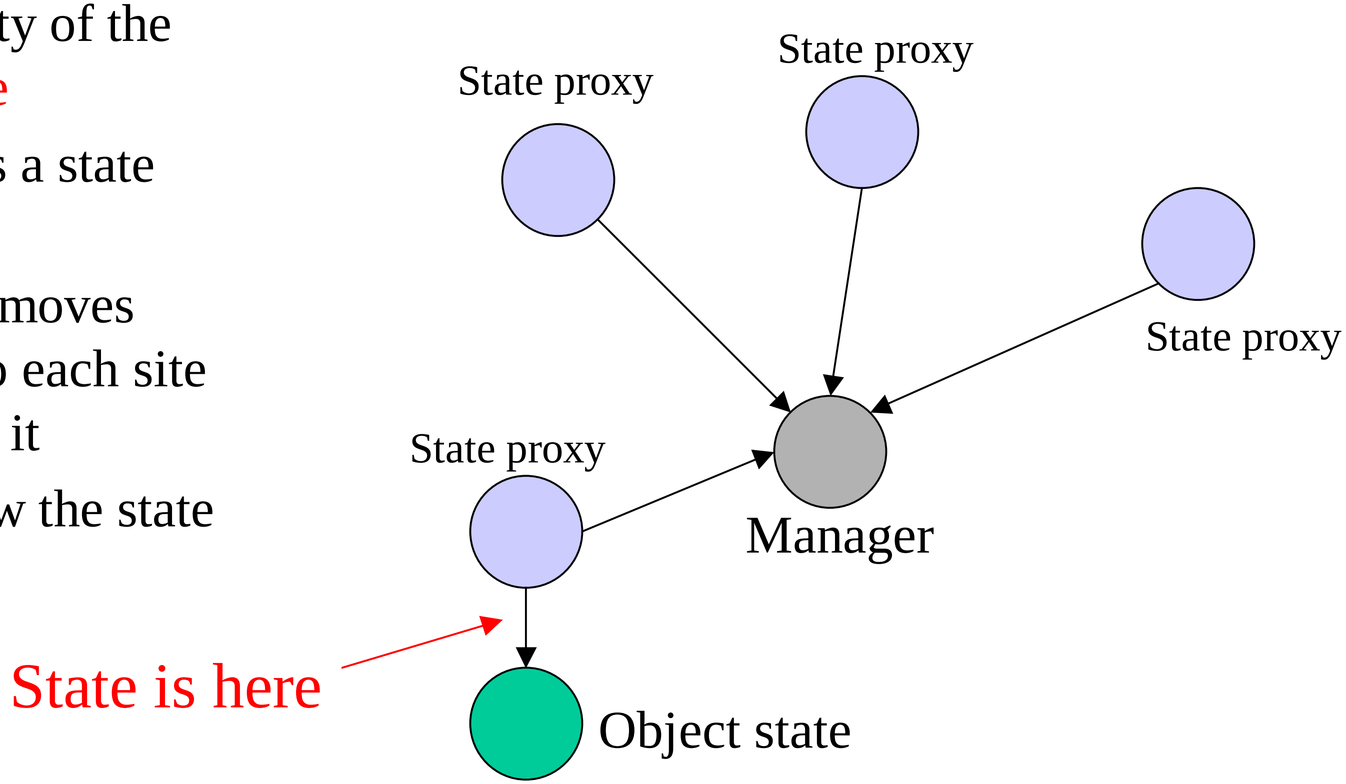


Cached (« mobile ») object (1)

- 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; does not need to be copied subsequently

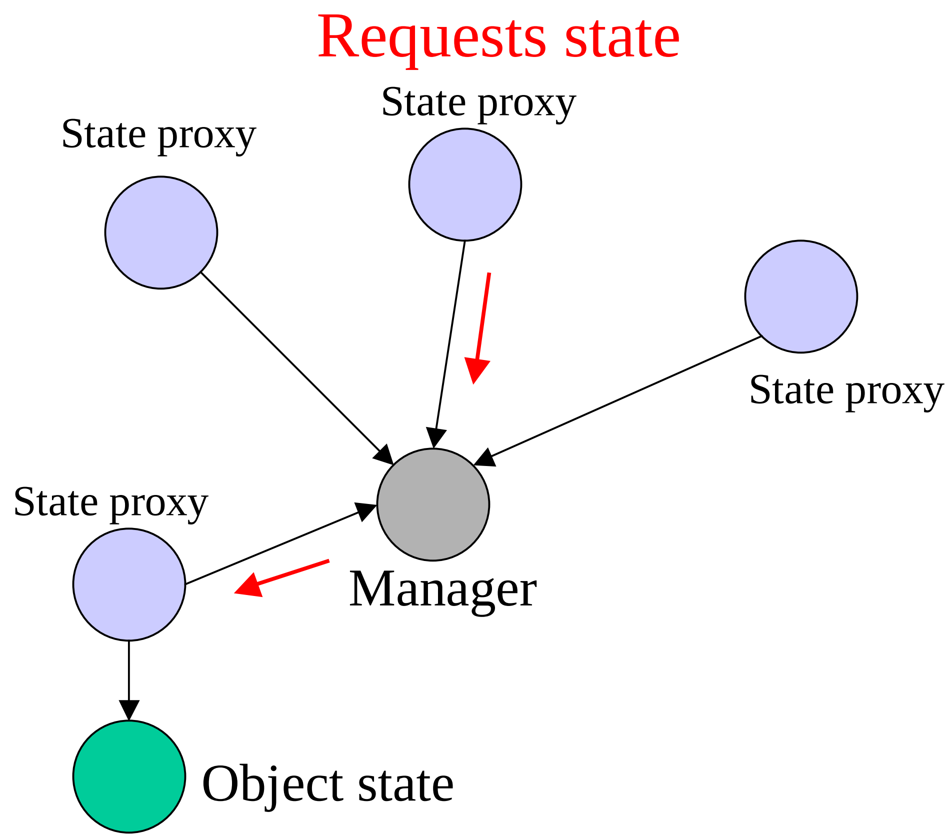
Cached (« mobile ») object (2)

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



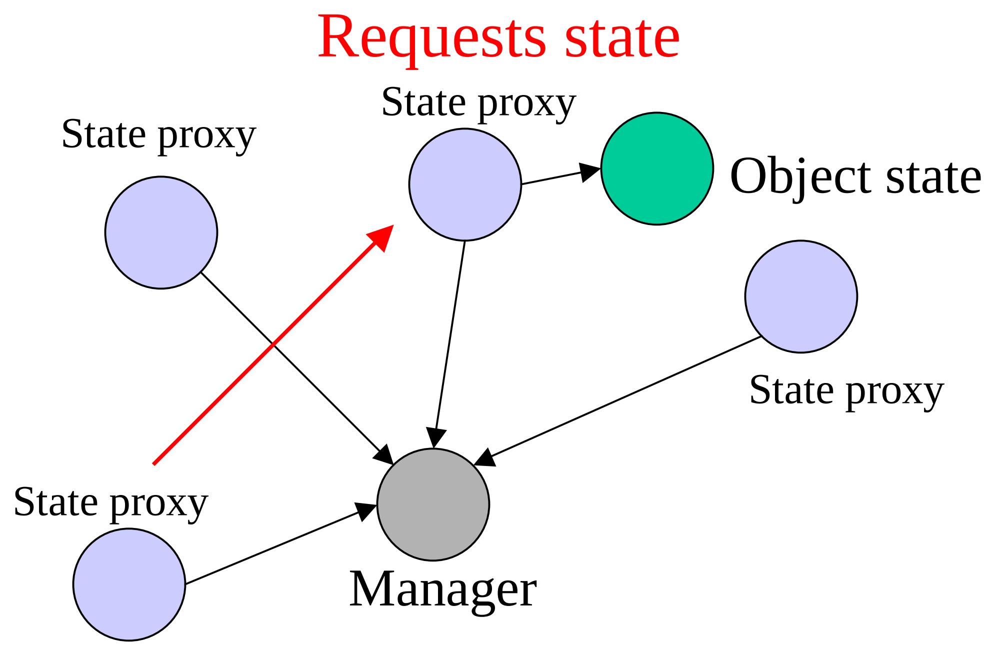
Cached (« mobile ») object (3)

- Another site requests the state
- 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



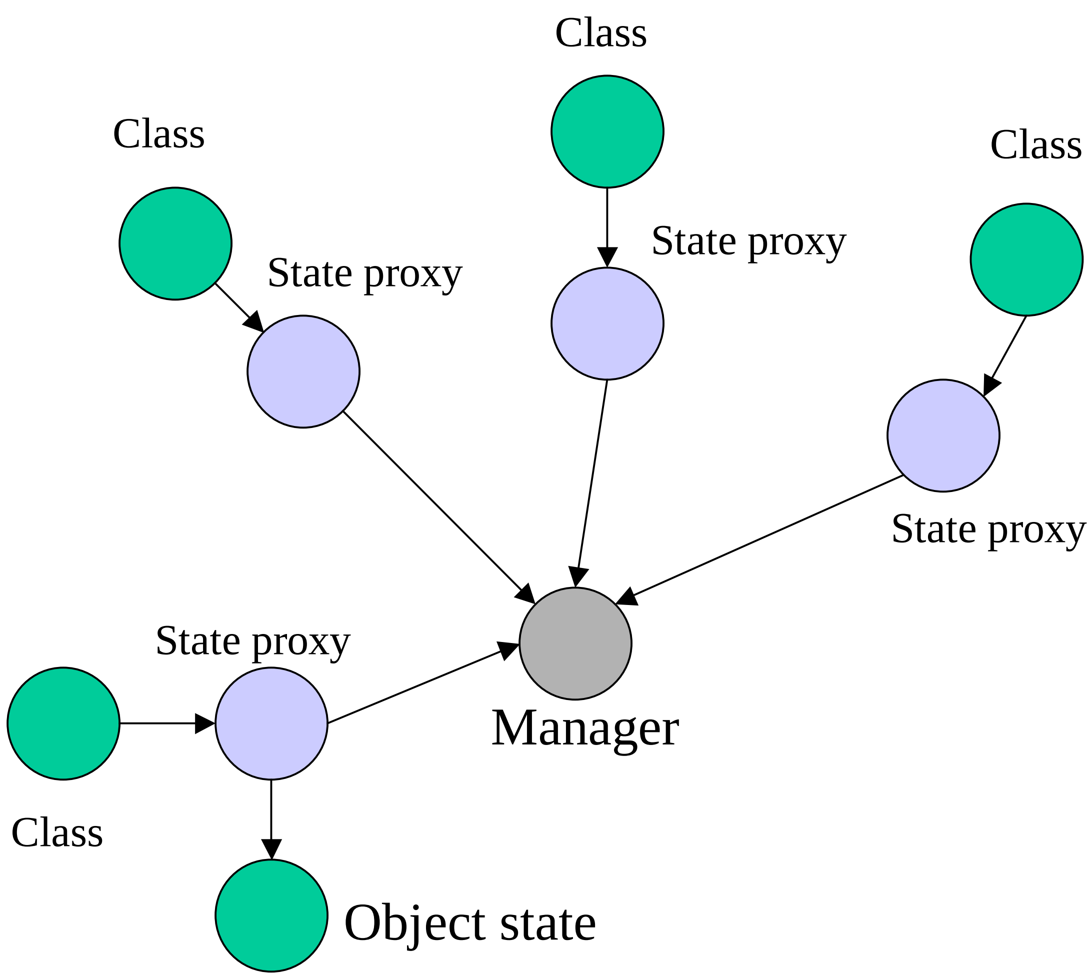
Cached (« mobile ») object (4)

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



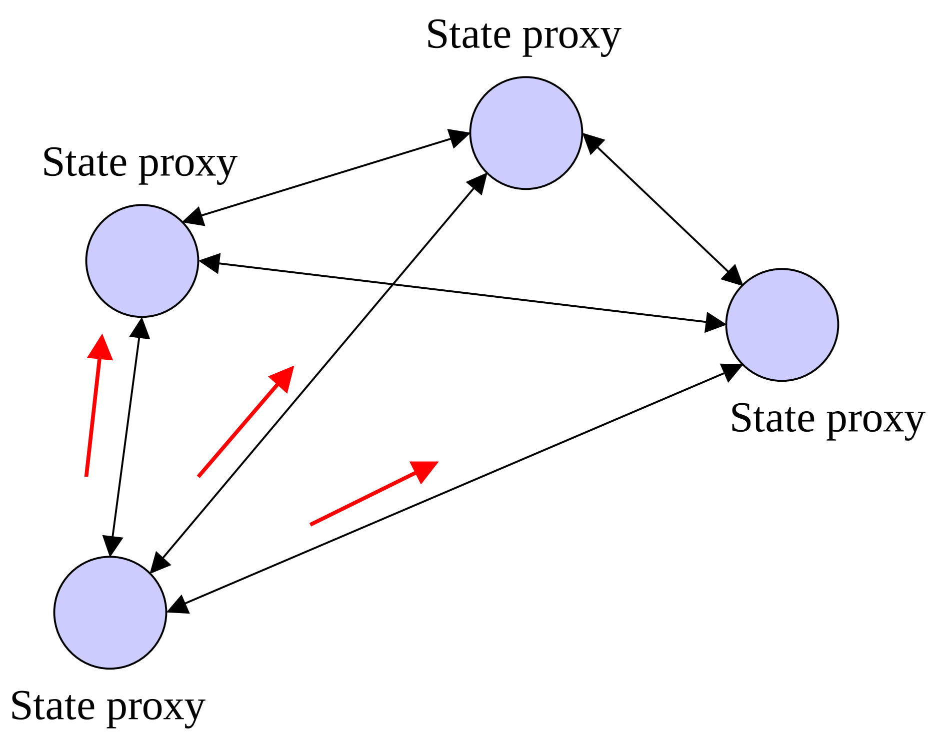
Cached (« mobile ») object (5)

- 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, each object has a closure that references both the class code and the state proxy
- Classes do not move; they are copied to each site upon first use of the object there



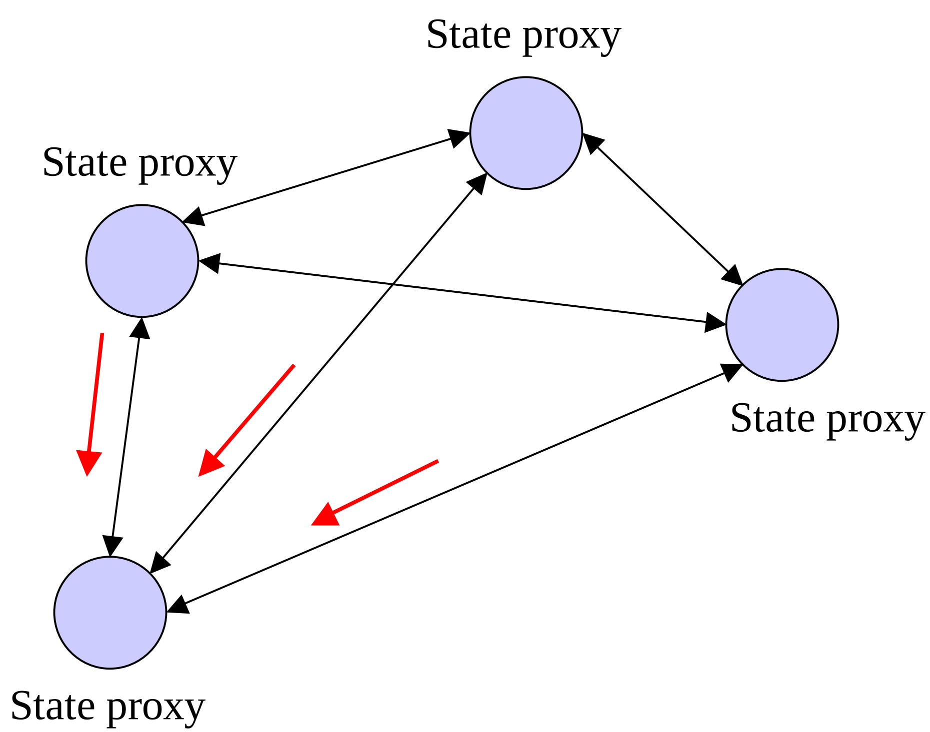
Invalidation-based object (1)

- An invalidation-based object is optimized for the case when object reads are needed everywhere 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



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 are 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, performance can be improved with none or minor changes to an existing program

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
```

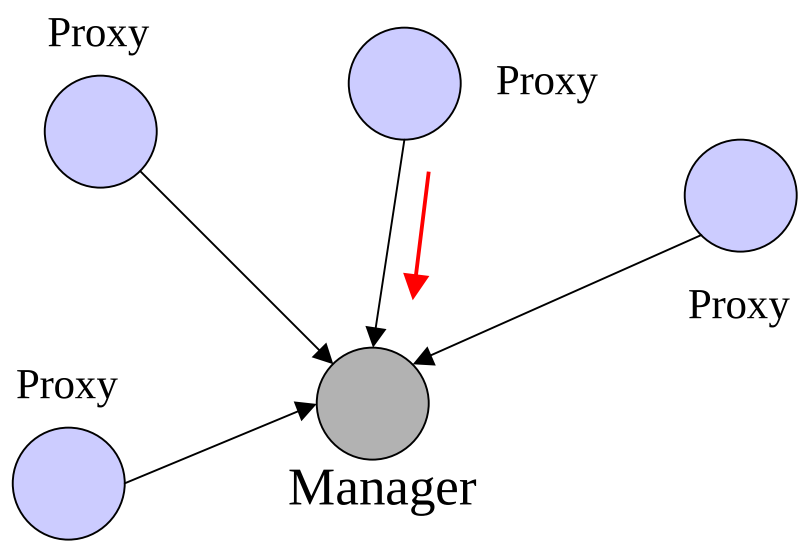
(binds X) (uses X)

- 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

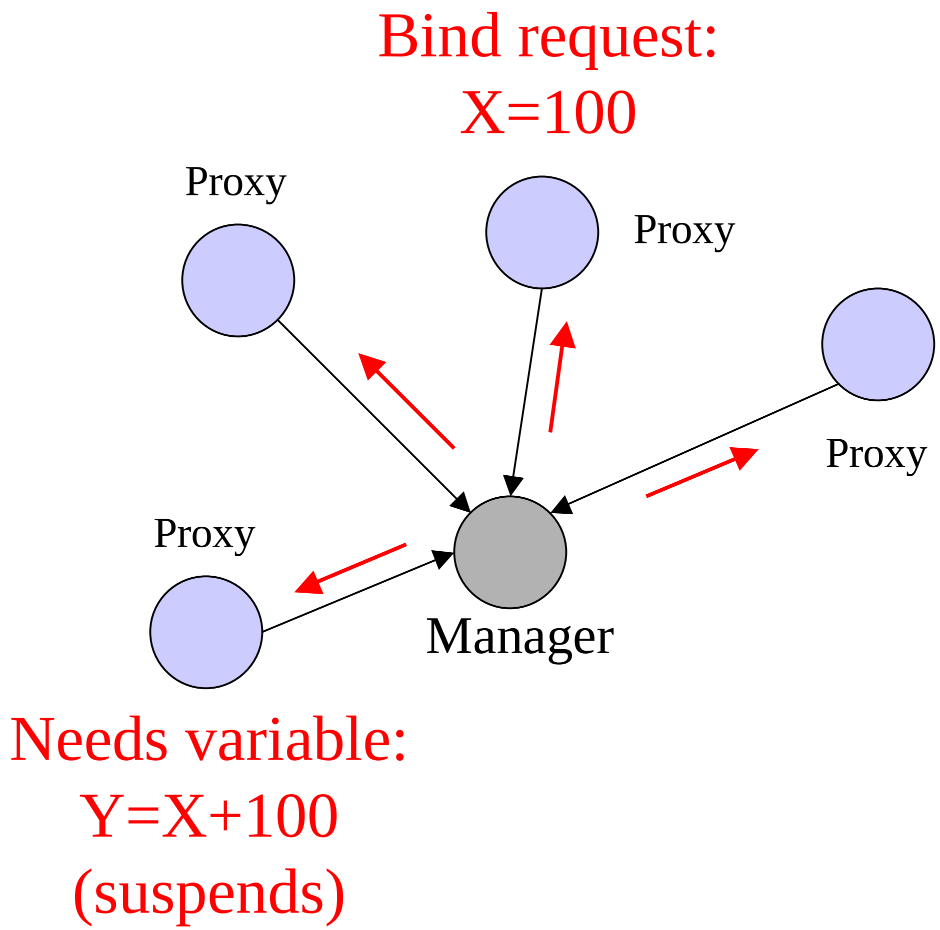
Bind request:
X=100



Needs variable:
Y=X+100
(suspends)

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 (but not much more)
  - What happens when there are two binding attempts: if second attempt is erroneous (conflicting bindings), exception is raised on guilty site
  - What happens with value-value binding and variable-variable binding: bindings are done correctly (operation is called « unification »)
- 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)

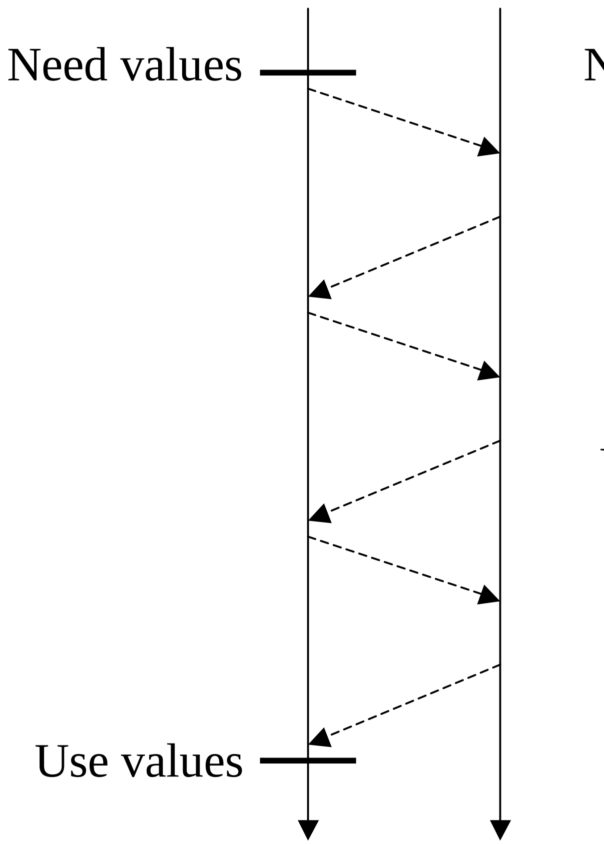
- Similar to an active object
  - Return values are passed with dataflow variables:

    ```
    C={NewAsync Cls Init}
    ```
    (local)

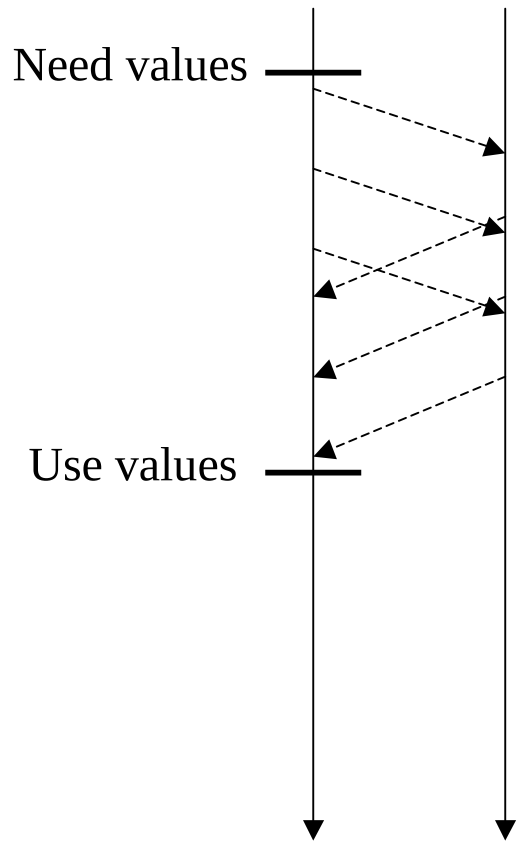
    ```
    {C get(X1)}
    {C get(X2)}
    {C get(X3)}
    ```
    (remote)

- 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

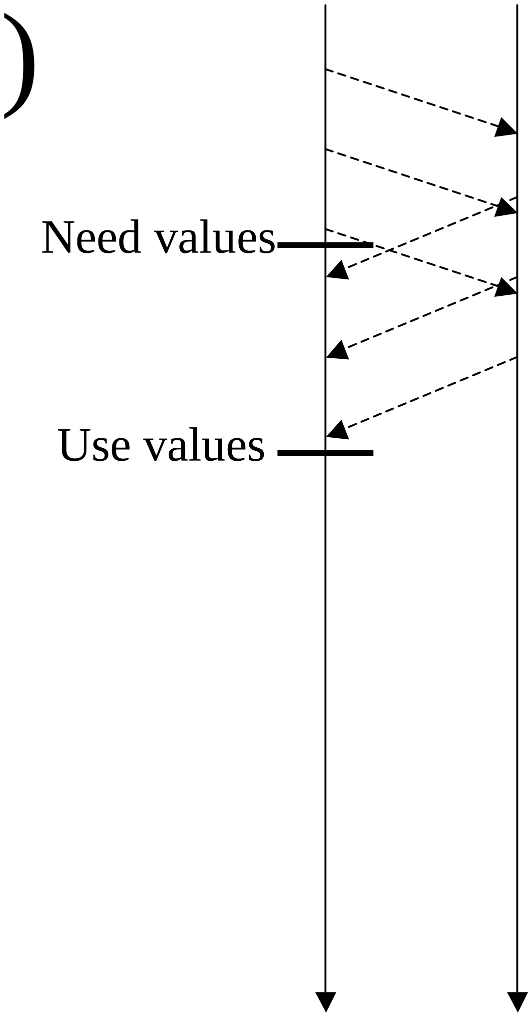
Dataflow variable and object invocation (2)



Call synchronously when needed



Call asynchronously when needed



Call asynchronously before needed

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

Fault tolerance

- Reflective fault detection
  - Reflected into the language, at level of single language entities
  - For now: 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
    - Our experience: asynchronous is better for building abstractions
- Fault tolerance
  - Build abstractions using reflective fault detection
  - 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
  - Algorithms for collecting these are complex
  - 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 system
  - Including stationary, cached mobile, asynchronous, and transactional object
  - Except for the invalidation-based object, which is not yet implemented

Conclusion and ongoing work

- With proper language semantics, network transparency becomes practical
  - Separation of functionality, distribution, and fault tolerance
  - More fault tolerance abstractions are being developed (better separation of concerns)
  - Study fundamental limits of network-transparent distributed computing
- Ongoing work: simplifying building distributed applications
  - Hook distribution and fault tolerance into the user interface with distributed widgets
  - Just a few lines of code for many fault-tolerant distributed applications
- Ongoing work: improved network layer
  - Visualization tool for observing all network behavior at high level of abstraction (« Distribution Panel » in Mozart 1.2.0)
  - Fine-grained multi-channel transport protocol
- Ongoing work: security
  - Capability security at the language level, supported cryptographically by implementation
  - Related to work on E language and system (Mark Miller et al)
- Projects starting in high availability, security, and peer-to-peer computing
  - We are looking for good people to join our team