Lecture 2: Theoretical issues

Contents

What is a coordination model

Historically, Linda was introduced as a new model for parallel programming, more flexible and high level wrt its competitors (“Linda Is Not aDA”)

It proved that it is possible to “think in a coordinated way” abstracting from low level mechanisms for concurrent, parallel, or distributed programming

It showed that a careful design can avoid to pay a performance price to use a high-level coordination model

It opened the way for a new reasearch area:
Coordination Languages and Models

A *coordination model* is an abstract (semantic) framework useful to study and understand problems in designing concurrent and distributed programs

“A coordination model is the glue that binds separate activities into an ensemble” [CarGel92]

In other words, a coordination model provides a framework in which the interaction of individual agents can be expressed.

This covers the issues of dynamic creation and destruction of agents, control of communication flows among agents, control of spatial distribution and mobility of agents, as well as control of synchronization channels and distribution of actions over time

Linda and open systems

Whereas Linda was born for batch (single user) parallel programming, its underlying coordination model, namely the tuple space, has been investigated as a model for open systems design, because of the following features:

⇒Uncoupling of agents
Senders and receivers using the tuple space as channel/repository do not know about each other

⇒Associative addressing
Linda agents use patterns to access data, namely they say *what* data they need rather than *how* it should be found.

⇒Non determinism
Associative addressing is intrinsicly non-deterministic, that is appropriate to manage information dynamically changing

⇒Separation of concerns
Linda was the first language to focus solely on coordination, proving that coordination issues are orthogonal to computation issues, that is useful to deal with legacy systems (seen as formed by components reusable and pluggable in novel software architectures)

Whereas computation deals with *algorithms*, coordination deals with *architectures* (configurations of agents)

Coordination architectures

Examples of coordination architectures are

- the client-server
- the peer-to-peer
- the master-worker
- the software pipeline
- the tuple space (shared repository)

We say that these are *software architectures* because their components are arranged in some special, well-defined, reusable structures that enact a specific coordinated behavior

Software designers are used to design a distributed software architecture using low-level communication primitives and/or special module configuration languages

Instead, we suggest that a software designer should have clear a coordination model, embedded in a coordination language, able to support a specific coordination architecture

Coordination models and languages

A *coordination model* offers mechanisms at least to control component generation/termination, (asynchronous) communication, multiple communications flows, multiple activity spaces; usually a coordination model consists of some coordination mechanisms that are added to a host language

Definition:
A *coordination model* is a triple (E,M,L), where:

- E are the *coordinable entities* : these are the active agents which are coordinated. Ideally, these are the building blocks of a coordination architecture.
  (eg. agents, processes, tuples, atoms, etc.)

- M are the *coordinating media*: these are the media enabling the coordination of interagent entities. They also serve to aggregate a set of agents to form a *configuration*.
  (eg. channels, shared variables, tuple spaces, bags)

- L are the *coordination laws* ruling actions by coordinable entities
  (eg. associative access, guards, synchr. constraints)

Definition:
"A *coordination language* is the linguistic embodiement of a coordination model" and consists of some coordination mechanisms that are added to a *host* (sequential) language

A coordination language should offer specific tools for optimizing coordination programs and reasoning on them

Coordination languages

In practice, a coordination language includes clearly defined mechanisms for communication, synchronization, distribution, and concurrency control

It is based on a formally defined coordination model and it is "independent" from any sequential language; however, it should be easily embedded in any programming language

• Linda ("shared tuple space")
  coordinable entities: active tuples
  coordination media: tuple space
  coordination laws:
    non blocking `out` of passive tuples;
    blocking `read`/`in` by pattern matching;
    complex `eval` semantics

• GAMMA
  coordinable entities:
    "chemical reaction" represented as condition-action pair
  coordination media: multiset
  coordination laws: fixpoint application of condition-action pairs

• Interaction Abstract Machines
  coordinable entities: objects as multisets
  coordination medium: forum
  coordination laws: a fragment of Linear Logic + broadcasting

Linda formal semantics

Linda was defined at Yale and implemented over several hw architectures without any formal semantics.

This caused some problems in porting Linda programs from an implementation to another

A formal semantics for Linda was firstly defined in Z [Butcher 90]. A formal semantics by Yale people was given in [Gelernter & Zuck 1997]

[Ciancarini et al 1994] studied a number of formal semantics, aiming at comparing the expressivity of some well known concurrent semantic models as a tool for the design of alternative language implementations

After having abstractly specified the Linda coordination model, we introduced, studied and compared the SOS, CCS, PetriNet, and CHAM semantics for Linda

Some researchers in York used the CHAM semantics to approach and model multiple tuple space extensions

[Busi et al 98] studied the Turing-equivalence of Linda

A formal specification of Linda

The following transition system specifies Linda coordination model [Ciancarini et al 1994]

Coordination entities:

Type names: Type = {int,char,…}
Typed values: Value = $\cup$ {$a{:}\tau, \perp{:}\tau \mid a \in V\tau$}
Passive tuples: Tuple = Value^i
Active tuples: Active = $(\text{Value} \cup \text{Process})^i$
Linda ops: Op = {eval(t) | t $\in$ Active} $\cup${out(s),rd(s),in(s) | s $\in$ tuple}
Linda processes: Process::= Γp,
Tuple space: TS = $\oplus${t:#[t]}

Coordination medium:

Tuple space:

Linda <Γ,→> where Γ = TS and → ‡ TS × TS

Coordination rules:

Process creation: $\forall t \in$ Active: {t'[i:eval(t).e]} → {t'[i:e],t}

Tuple creation: $\forall t \in$ Tuple: {t'[i:out(t).p]} → {t'[i:p],t}

Tuple copying: $\forall s,t \in$ match: {t'[i:rd(s).p],t} → {t'[i:t.p],t}

Tuple removal: $\forall s,t \in$ match: {t'[i:in(s).p],t} → {t'[i:t.p]}

Local transition: $\dfrac{p' \to p''}{\{t'[i:p']\} \to \{t''[i:p'']\}}$ $\dfrac{ts' \to ts''}{ts \oplus ts' \to ts \oplus ts''}$

A Linda calculus

The transition system Linda is defined independently of the host language and any implementation concern: it is a specification of the coordination model underlying Linda

In order to have a framework useful for implementation design, we have also introduced a Linda calculus

P::= `eval`(P).P | `out`(t).P | `rd`(t).P | `in`(t).P | X | recX.P | P[] | end

Interleaving transition system SOS style

eval)	M ⊕ `eval`(P).P' → M ⊕ P ⊕ P'
out)	M ⊕ `out`(t).P' → M ⊕ P ⊕ t
rd)	M ⊕ `rd`(s).P' ⊕ t → M ⊕ P [t/s] ⊕ t, if (s,t) ∈ match
rd)	M ⊕ `in`(s).P' ⊕ t → M ⊕ P [t/s], if (s,t) ∈ match
rec)	$\dfrac{M \oplus P[recX.P/X] \rightarrow M \oplus P'}{M \oplus recX.P \rightarrow M \oplus P'}$
leftchoice)	M ⊕ P[]P → M ⊕ P
rightchoice)	M ⊕ P[]P → M ⊕ P'
end)	M ⊕ `end` → M

Multistep (parallel) transition system SOS style

par) $\dfrac{M1 \rightarrow M1' \quad M2 \rightarrow M2'}{M1 \oplus M2 \rightarrow M1' \oplus M2'}$

Some theoretical issues in Linda calculi

Some effort has been devoted to compare the expressiveness of different Linda calculi obtained varying the semantics of base operations

Example: Different semantics for:

- `out` operator (ordered vs unordered) [Busi et al]
- parallel composition (interleaving vs maximal parallelism) [Gabbrielli et al]
- introducing time in Linda

Choices in designing a semantics for a Linda-like language

[Campbell et al. 96] have studied and compared a number of formal semantics for Linda, and found a number of options in describing its coordination model

• simple matching / constrained matching?

• `eval` is the only means of process creation?

• active tuples actually exist?

• active fields in an active tuple are executed in parallel?

• active tuples are first class objects?

• bulk retrieval operations, if possible, are atomic?

• tuple space name always specified?

• tuple spaces are first class objects?

• scoping hierarchy of tuple spaces?

• garbage collection of tuple spaces?

• a global (root) tuple space as operating environment?

Coordination based on multiset rewriting

Conventional languages for distributed programming are based on primitives like `send/receive` which

- distinguish between process, data, msg, and channel
- require a synchronous style to simplify programs
- require an id: correspondent name, mailbox, channel

A multiset is a versatile data structure which can be used:

• to represent and handle a process (object) state
• to represent and handle a channel state
• to represent and handle the state of a set of threads

Whereas even Petri Nets can be represented as multiset rewriting systems, a computing model called CHAM (chemical abstract machine) [Berry&Boudol 93] best represents non sequential computations based on multiset rewritings

Linda can be semantically mapped on the CHAM, and most coordination languages can be easily mapped on it
(you need a coordination language to implement a coordination model!)

GAMMA

GAMMA (General Abstract Model for Multiset mAnipulation) [Banatre & LeMetayer 90] is a coordination model whose main data structure is the multiset (or bag) and whose unique control structure is the Γ operator

```
Γ((R1,A1),…,(Rm,Am)) (M) =
        if ∀i ∈ [1,m], ∀x1,…,xn ∈ M, ~ Ri(x1,…,xn)
        then M
        else let x1,…,xn ∈ M, let i ∈ [1,m] such that Ri(x1,…,xn) in
        Γ((R1,A1),…,(Rm,Am)) ((M-{x1,…,xn}) + Ai(x1,…,xn))
```

The notation {…} represents multisets; (R_i,A_i) are pairs of closed functions (no global variables) specifying reactions. The effect of (R_i,A_i) on multiset M is to replace in M a subset of elements $\{x_1,\ldots,x_n\}$ such that $R_i(x_1,\ldots,x_n)$ is true by the elements of $A_i(x_1,\ldots,x_n)$

Γ is a fixpoint operator: reactions continue until no new reaction is possible (implicit termination condition).

All possible reactions are fired: this is the source of parallelism in GAMMA.

Examples:

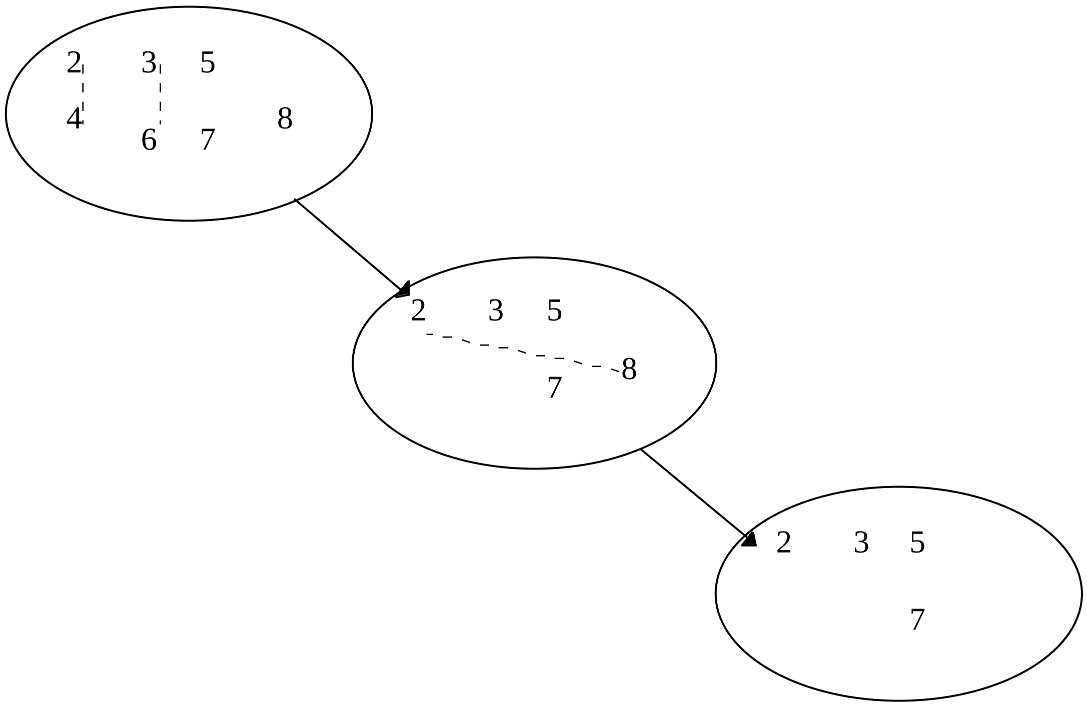
sum_all: $x,y \rightarrow x+y \Leftarrow \text{true}$
max: $x,y \rightarrow y \Leftarrow x \leq y$
sort: $(i,v),(j,w) \rightarrow (i,w),(j,v) \Leftarrow (i>j) \wedge (v<w)$

Programming by rewriting a multiset

The sieve of Eratosthenes can be written as follows:

sieve: x,y $\rightarrow$ y $\Leftarrow$ multiple(x,y)

sieve({2,3,4,5,6,7,8}):



GAMMA Calculus

GAMMA has been enriched with a calculus [Hankin & al] including some program composition operators:

$P1 \circ P2$ (sequential) and $P1 + P2$ (parallel)

Example1:
$\Gamma1$: $n \rightarrow n-1, n-2 \Leftarrow n>1$
$\Gamma2$: $n \rightarrow 1 \Leftarrow n=0$
$\Gamma3$: $n,m \rightarrow n+m \Leftarrow$ true

$\Gamma3 \circ \Gamma2 \circ \Gamma1$ computes the n-th Fibonacci number;
we can prove: $\Gamma3 \circ \Gamma2 \circ \Gamma1 = \Gamma3 \circ (\Gamma2 + \Gamma1)$

However, the original GAMMA calculus presents some semantics problems, that have been studied and solved in [Ciancarini et al. 95]

Example2:
sort: *match* ◦ *init*
where *init*: (x → (1,x) ⇐ integer(x))
match: ((i,x),(j,y) → (i,x),(i+1,y) ⇐ (x≤y and i=j))

To have the equivalence *match* ◦ *init* = *match* + *init*
a synchronized termination of *match* and *init* in parallel combination is required

The Chemical Abstract Machine

A tuple space is actually a multiset of tuples; abstractly, a multiset is also called *bag*

We could imagine an observer that sees what happens in a tuple space: he could describe what he sees as *a chemical soup* (namely a solution) which is *active*, namely molecules in the solution appear and disappear

A Chemical Abstract Machine [Berry Boudol 93] is a triple (G, C, R) where

• G is the grammar generating C
• C is the set of configurations (molecules)
• R is a set of rules: *condition* x bag(C) x bag(C)

where *condition* is a logical expression on molecules in the bags, which respectively have to be deleted (preconfiguration) and added (postconfiguration)

Rules can fire concurrently if they do not interfere; if some rules conflict on the same molecules, a non conflicting subset is chosen non deterministically to react

Molecules are defined as terms of a specific algebra;
solutions are finite multisets of molecules;
a solution can be enclosed in a membrane, denoting a separate subsolution

A CHAM for Linda

We start from a toy Linda formalism called Linda calculus.

P::= eval(P).P | out(t).P | rd(t).P | in(t).P | X | recX.P | P[]P | end

The three new productions are useful to model recursive processes and local nondeterministic choice.

par)	M1 $\oplus$ M2 $\leftrightarrow$ M1, M2
eval)	eval(P).P’ $\rightarrow$ P,P’
out)	out(t).P $\rightarrow$ P,t
rd)	rd(s).P,t $\rightarrow$ P[t/s],t *if (s,t)* $\in$ *match*
in)	in(s).P,t $\rightarrow$ P[t/s] *if (s,t)* $\in$ *match*
rec)	recX.P $\rightarrow$ P[recX.P/X]
leftch)	P[] P’ $\rightarrow$ P
rightch)	P[] P’ $\rightarrow$ P’
end)	end $\rightarrow$

We have also defined pattern matching in CHAM [CJY94].

This semantics is simple and fully distributed; it can be used to study other coordination languages and novel mechanisms

Implementing the CHAM

The CHAM itself has been suggested as coordination language for a MIMD architecture
[Ma et al., 1996 - Australia]

They see the CHAM as a refinement of Gamma

```
% parallel summation
initialization
   m = 10, m= 20,  m = 15
reaction rules
   x,y leadsto z by {z = x+y}

% sleeping barber problem
initialization
   [i:1..N]::chair=TRUE; bsp=TRUE
reactionrules
   pin,bsp leadsoto pcut,bwk;
   pin,chair leadsto pwt when (~bsp)
   pcut, bwk leadsto pout, bfin;
   pwt, bfin leadsto pcut,chair,bwk;
   bfin leadsto bsp when (|pwt|==0)
```

This CHAM dialect has been implemented over an AP1000, with 128 nodes.

Designing a distributed runtime using the CHAM

The CHAM has been used to describe and study the runtime systems of coordination languages:

• Linear Objects [Andreoli et al 1993]

The main issue is the description of broadcasting communication typical of LO

• Facile [Leth and Thomsen 1994]

The main issue is the description of a distributed execution management system necessary to implement Facile over a network

• Java [Ciancarini and Laneve 97]

We have studied the run time behavior of concurrent/distributed Java programs

A list of coordination models

Classic OS theory:
- Shared Data / semaphores and monitors
- Message passing / remote procedure calls

AI coordination architectures
- Blackboard [Nii, Bisiani & Forin]
- KNOS [Tsichritzis & Fiume & Gibbs & Nierstrasz]

Models for non imperative languages
- The Kahn-McQueen model
- Actors [Hewitt & Agha]
- Unity/PCN language model [ManyChandy et al.]
- Concurrent constraint logic prog. [Shapiro, Saraswat]

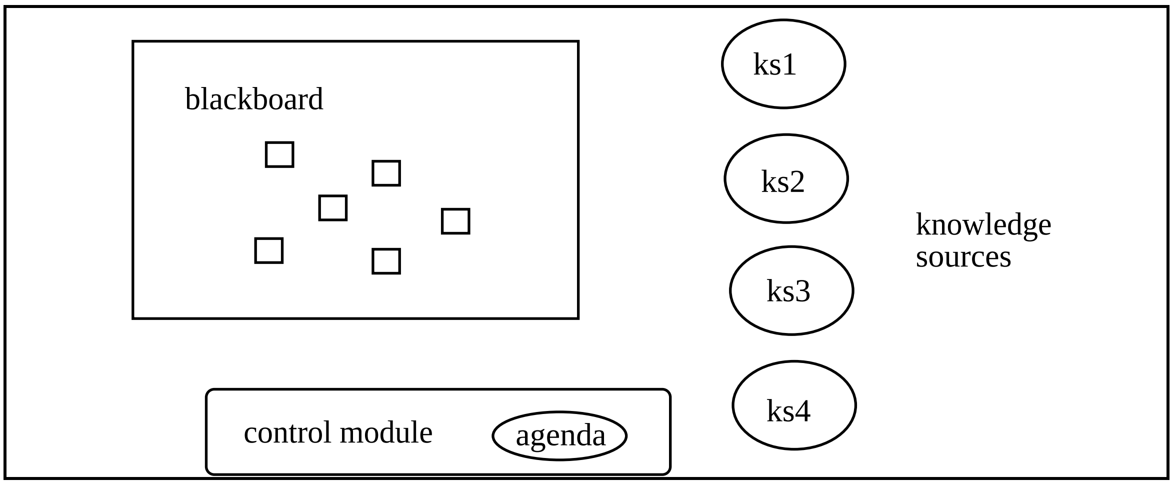
Event-driven coordination languages
- Manifold [Arbab]

Coordination models based on multiset rewriting
- Gamma (and CHAM) [Banatre & LeMetayer; Berry&Boudol]
- Multiple tuple spaces [Gelernter, Hupfer]
  - Bauhaus [Carriero & Gelernter & Hupfer]
  - PoliS [Ciancarini et al.]
  - Interaction Abstract Machines [Andreoli & Pareschi]

Blackboard

The *blackboard* software architecture [Nii 86] was introduced to design some AI applications in which

- a number of coordination entities called “*knowledge sources*” cooperate to solve a problem
- described by data contained in a coordination medium called the “*blackboard*”, controlled by an *agenda* module;
- the control module in early applications was sequential, but it is possible to distribute both the blackboard and the activities included in the agenda

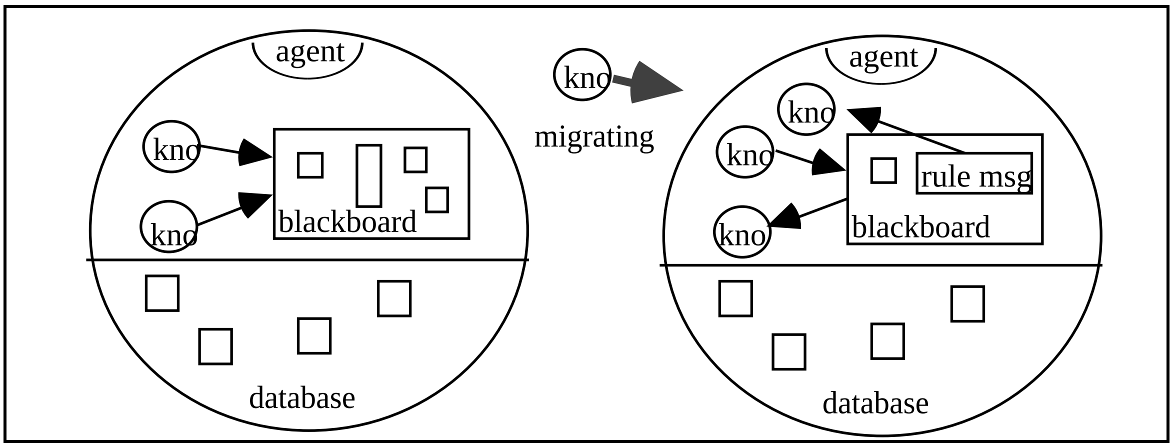


A physically distributed logically shared data structure is abstractly separated from processes that can manipulate it; in Linda, for instance, the distributed data structure is contained in a Tuple Space, that is a multiset of tuples; processes produce/consume tuples and create other processes

KNOs

KNOs (KNowledge acquisition, dissemination, and manipulation Objects) [Tsichiritzis 1987] is a coordination model introduced for knowledge based systems with multiple agents that can negotiate, cooperate and learn

A set of cooperating KNOs exist within a context (typically, a context is associated to a workstation); KNOs communicate reading or writing message on a blackboard
A KNO can move to another context (migration); it can modify itself accepting code for new operations (learning)



KNOs behaviors can be written using a LISP-like notation:

```
(rule <rule-name> (trigger <trigger-condition>)
  (action <action-series>))
```

Actions are of five different types:
- local actions (on local variables)
- communications (using the blackboard)
- spawn, die, move, freeze, unfreeze a KNO
- learning actions (send or receive new behavior rules)
- limb actions (grow, kill, ship, teach, unteach a limb)

A limb is a KNO generated by another KNO (head). A head and its limbs can span different contexts

Multiple Tuple Spaces

C-Linda was designed for simplifying programming on different parallel architectures, supporting a high degree of portability; however, C-Linda offers good support also for system programming of distributed systems

“Normal” Linda applications: programs explicitly exploiting massive parallelism, typically with a master/worker architecture (“closed” Linda programs)

A single Tuple Space has the problem that it has to be “closed”, i.e. it must be used by a single parallel computation (otherways processes of different computations could interfere with each other);

An obvious extension to the Linda model is based on Multiple Tuple Spaces

The multiple tuple spaces model is especially useful for “open” Linda programs, in which several users interact with a Linda program that coordinates them

Multiple tuple spaces [Gelernter 89] can offer a natural mechanism of modularity; the concept is also useful for multiparadigm systems; persistent tuple spaces can be defined in this framework

There are several proposals for MTS models:
• Paradise, PoliS, KLAIM
• Interaction Abstract Machines and CLF
• Bauhaus
• LIME

PoliS

PoliS [Ciancarini et al. 1997,2000] tries to be more faithful to Linda than Paradise: it adds a new operation to create a named “empty” tuple space:

`tsc(tuple_space);`

PoliS also extends `out` operations to deal with remote creation of tuples (eg.: `out(tuple)@tuple_space`);

A “meta” tuple space takes care of these messages, so that generative communication is used for interspace coordination as well

A closed PoliSpace is similar to a Linda program: a number of tuple spaces start and run until completion of the global task

"Closed" PoliS programs are intended for massive computations

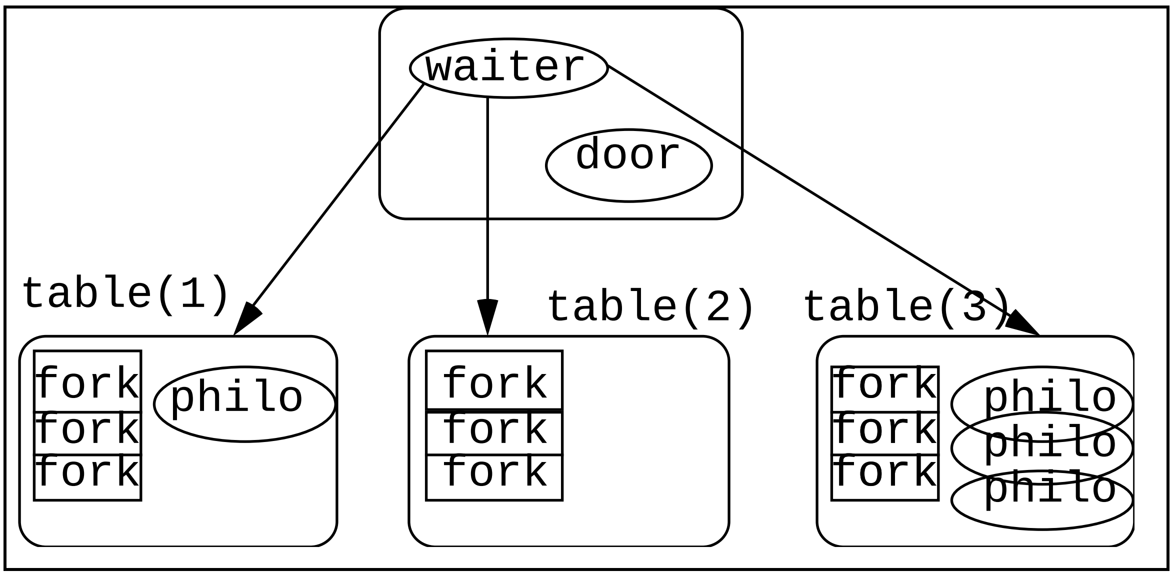
An open PoliSpace, i.e. an interactive distributed program, includes a number of tuple spaces and some spaces called “shells” (or “roles”); a shell is an “interactive” tuple space, where the user can directly put tuples (a shell is an interaction point between the PoliSpace and the external environment)

An open PoliSpace is a useful model for groupware applications, e.g.:
- a distributed multiuser sw dev. environment,
- an electronic mail system,
- a financial simulation of stock exchanges,
- a Web-based card playing system

PoliS

A PoliSpace can be seen as a “city”, i.e. a set of distinct spaces; each space contains several agents

Agents are independent computing entities; they can output objects to any space they know; they can only look in their own space for input; the interspace communication mechanism is generative communication through a meta tuple space



We have developed PoliS as a specification language

We have studied a TLA based logic to reason by theorem proving on PoliS specification documents;
we have studied model checking to study properties of systems including mobile agents

Interaction Abstract Machines

The model of Interaction Abstract Machines (IAM) [ACP 93] has been introduced to describe interactions among independent, locally defined subsystems

IAMs combine dual concepts in distributed problem solving, such as blackboards broadcast communication, which are exploited to account for, respectively, the tight integration and the loose integration of system components

In the IAM metaphor, the state of a (single) agent is represented as a set of particles evolving within a determined (computational) space.

Each particle represents a resource, and we assume that the particles are in a perpetual ``Brownian" motion, so that they may randomly collide together.

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Single agent IAM

In a single-agent IAM, the state of the agent is represented as a multiset of resources. It may evolve according to rules which rewrite the multiset

In fact, a single-agent IAM can be seen as an elementary blackboard system:

- the state of the agent captures the content of the blackboard at any time;
- the rules (or methods) represent the different knowledge sources which interact through the blackboard:
    - the head of a rule specifies resources which are taken from the blackboard;
    - the body specifies resources which are output to the blackboard

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Multi-agent IAM

To build multi-agent systems, we add new primitives for the creation and termination of agents

the body of a method may now be formed of 0 or more multisets of resources instead of just one unique multiset.

The generated multisets become completely independent agents and start evolving autonomously.

The universe (of computation) now consists of several concurrent spaces of the kind introduced previously

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Bauhaus

Bauhaus [Gelernter et al 95, Hupfer 96] is a generative, uncoupled, associative memory coordination model, like Linda.

However:

• Bauhaus is based on (nested) multisets
• matching is based on set inclusion
• primitives return multisets

Example: a multiset in Bauhaus
M = `{a, b, {b}, X, {c, {d, e}}}`

Bauhaus generalizes Linda in the following ways:
- tuples and tuple spaces are both replaced by msets
- tuples and tuple templates disappear
- passive and active data objects are unified

One multiset matches another if it is included in the other

Bauhaus has been explored in [Hupfer 1996], and has been used to implement a number of groupware applications

Bauhaus operations: in and out

All Bauhaus coordination programs are evaluated wrt a universal coordination space (ucs) which is the basic mset

Example 1 (`in`). Suppose that the current ucs is

```
{a,b,{b},X,{c,{d,e}},{c,Y},Z}
```

where X,Y,Z represent processes (live msets)

Let X be a process executing the following code:

```
mset m;…; i=in({c});
```

There are two possible results:

- `{a,b,{b},X,{c,Y},Z};   i={c,{d,e}}`
- `{a,b,{b},X,{c,{d,e}},Z}; i={c,Y}`

Example 2 (`out`). Suppose that the current ucs is

```
{b,{b},X,{c,{d,e}},Z}
```

Let X be a process executing the following code:

```
mset m;…; i=out({v,{w}});
```

The result is:

```
{a,b,{b},X,{c,Y},Z,{v,{w}}};
```

Bauhaus operations: move

Bauhaus adds to Linda’s classic operations `in`/`read`/`out` (extended to deal with multisets) the `move` operation, which is in some way the opposite of `in`: a process moves to a matching multiset (if available; otherways it blocks), so implementing a form of associative migration

Using `move`, processes can move up or down in the ucs one level at time

Example 3 (`move`). Suppose that the current ucs is

```
{a,b,{b},X,{c,Y},Z,{v,{w}}};
```

Let X execute the following code: `move({v});`

The result is: `{a,b,{b},{c,Y},Z,{v,{w},X}};`

It is also available the non blocking form `movep`

The hierarchical and persistent nature of multisets makes them an attractive means of storing Web documents

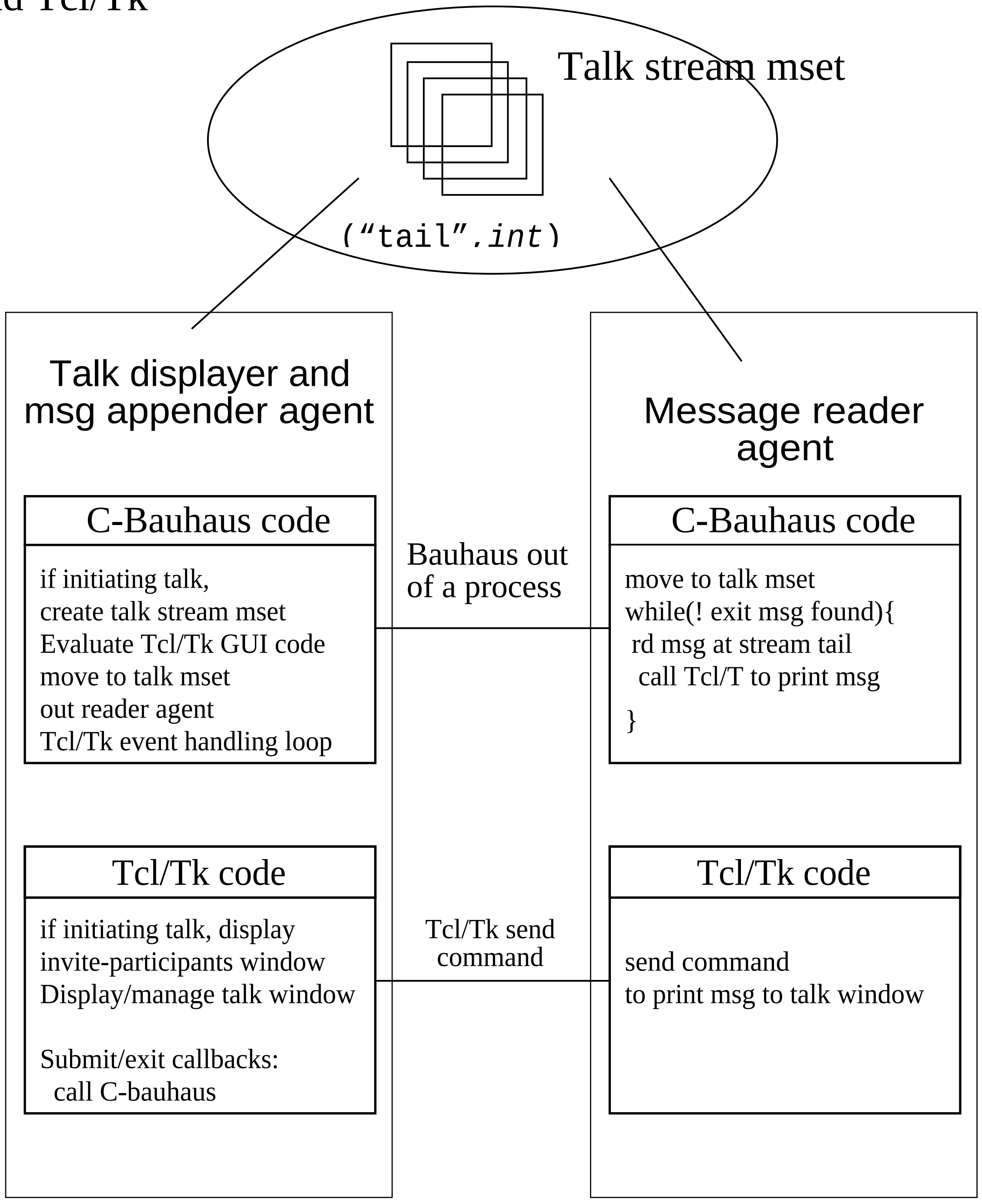
Both a Web server and browser have been implemented emulating Bauhaus coordination using Netscape and CGI

Each page offers 4 navigational commands:
up, top, back, down

The pages are active, that means for instance that agents which are visiting them are visible by other agents

A conversation stream system

As an example of Bauhaus coordination design, we describe a multiuser conference system implemented in C-Bauhaus and Tcl/Tk



Software architecture of conversation stream system

Coordination and I/O

Agent Agents are active, self--contained entities performing actions on their own behalf.

Action Actions can be divided into two different classes:

- Inter--Agent actions: these actions involve different agents. They are the subject of coordination models.
- Intra--Agent actions: these actions are performed by a single agent to perform computation as well as all communication outside the coordination model, like primitive I/O operations or interactions with users.

Coordination consists of managing the inter--agent activities of agents collected in a configuration.

Configuration a *structured* collection of interacting agents

Remark
In general, one could argue that I/O with the operating environment can easily be subsumed by a coordination model; however, this is true only to some extent.

Real-world applications have to fit into environments with agent-like user interfaces and I/O devices which do not adhere to any clearly defined coordination model

In order to integrate such interaction into a system of coordinated agents in a clean way, it is preferable to introduce specialized agents which play the role of interfaces between the world of coordinated agents and the outside environment

Internet programs are distributed and mobile

New computing paradigms based on code distribution and mobility need novel specification and programming languages

A key issue when an application includes mobile components is how to design its *architecture*, which can be decomposed in at least three different layers:

- The *physical network* layer, made mostly of *immobile hosts* and reliable and fast connections, where a mobile entity consists of a piece of hardware using a connection usually unstable (e.g. wireless) and with low bandwidth.

- The *middleware network* layer, made of *abstract machines* (e.g. a JavaVM, an XWindow server, etc.), where a mobile entity consists of a whole process or a service migrating from a host to another host.
  Problems at this level are resource management (e.g. load balancing) and service reliability (e.g. security)

- The *logical network* layer, made of application code scattered over the middleware network, where a mobile entity consists of an agent migrating from an abstract machine to another one. A problem at this level is how such a mobile entity can cooperate with other entities in the application

Coordination and mobility

Coordination models differ mostly in the way they control interaction: for instance, different models could offer different kinds of **mobility**:

- *planned*: an agent's itinerary across some locations is statically predefined;
- *spontaneous:* an agent's itinerary is not statically predefined, but the next location is computed by the agent itself at run-time;
- *controllable:* a migration is forced by an authority in some location, using some I/O mechanisms to communicate with a remote agent. Interestingly, there are two types of controllable mobility: *sender-controlled* and *receiver-controlled*.

Different kinds of mobility require different coordination models

Coordination and mobility

The issue of coordination mechanisms for mobile agents has been studied expecially in the context of environments for network-aware programming

Multiple Tuple Spaces are natural coordination media for both mobile code (Java) and mobile agents (code+state)

The following proposals differ in the coordinable entities, in the mechanisms used to access the tuple spaces, and in the possibility of extending the coordination laws

Details are discussed in [COZ99]

System	Coordinables	Media	Language	Laws
JavaSpaces	JavaAgents	TS	Java+Linda	Fixed
Lime	MobileAgents	Local and global TS	Linda+asynch primitives	Fixed
MARS	Java Agents	Network aware TS	Java+Linda	Programmable (in Java)
PageSpace	Agents+ Services	Network unaware TS	Java+Linda	Fixed
TSpaces	Agents	Network unaware TS	Linda+ user-defined primitives	Programmable (Overriding)
TUCSON	Information agents	Network aware TS	Logic oriented Linda	Programmable (in Prolog)
WCL	Agents, applications	Automatic reallocation	Linda+asynch primitives	Fixed
KLAIM	Kprocesses	TS	Java+Klaim	Fixed

Conclusions

Coordination models are a new exciting research field

Coordination models are an important tool for a new class of distributed applications, in which several agents (humans, tools, programs) have to be coordinated

There are several questions that are being addressed:

⇒ which coordination mechanisms are more expressive and useful?

⇒ which semantic models should be used to study such mechanisms?

⇒ which implementation techniques are best?

⇒ which software architectures match some specific coordination requirements?

⇒ which programming logics can be used to reason about coordination programs?

⇒ which new applications can be developed, which exploit the new technology?