Introduction to the ToolBus Coordination Architecture

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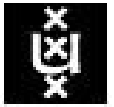

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Road map

- The problem: component interconnection
- History & requirements
- Terms, types & matching
- The ToolBus architecture
- ToolBus scripts (Tscripts)
- Larger examples
- Implementation issues
- Conclusions

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The problem: component interconnection

- Systems become heterogeneous because we want to couple existing and new software components
  - different implementation languages
  - different implementation platforms
  - different user-interfaces
- Systems become distributed in local area networks
- Needed: interoperability of heterogeneous systems

Component interconnection: reasons

- Reusing existing components decreases construction costs of new systems
- Decomposing large, monolithic systems into smaller, cooperating components increases
  - modularity
  - flexibility

Component interconnection: issues

- Data integration: exchange of data between components
- Control integration: flow of control between components
- User-interface integration: how do the user-interfaces of components cooperate?

Data integration

- Data representations differ per
  - machine: word size, byte order, floating point representation, ...
  - language implementation: size of integers, emulation of IEEE floating point standard, ...
- How can we exchange data between components:
  - integers, reals, record => linear encoding
  - pointers => impossible in general

Data integration

- Assume a common representation R
- For each component C_i (with data domain D_i) there exist conversion functions
  - $f_i : D_i \rightarrow R$ and $f_i^{-1} : R \rightarrow D_i$
  - Convert a value d_i from C_i to C_j by $f_j^{-1}(f_i(d_i))$
- Examples: IDDL, ASN-1, XML, ...
- ToolBus uses ATerms as common representation

Control integration

- Broadcasting: each component can notify other components of state changes
- Remote procedure calls: components can call each other as procedures
- General message passing: the most general approach
- In the ToolBus Tscripts are used to model the interactions between components

User-interface integration

- The ToolBus does not address user-interface integration as separate issue but can be used to achieve it

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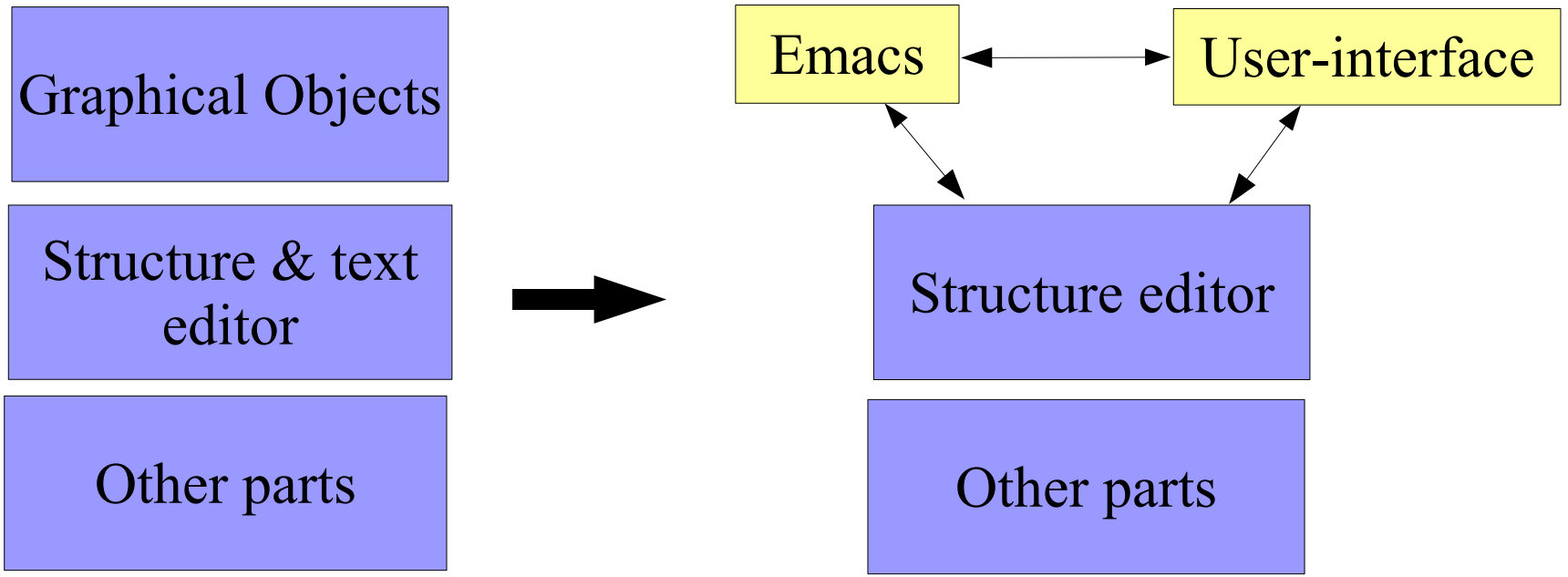
Brief history of the ToolBus

- In 1992 the first implementation of the ASF+SDF Meta-Environment was completed:
  - 200 KLOC Lisp code
  - Monolithic
  - Hard to maintain
- ... all traits of a legacy system

Time line

- 1992: Unsuccessful decomposition experiments
- 1994: First generation: ToolBus
- 1995: Second generation: Discrete time ToolBus
- 2001: Meta-Environment based on ToolBus
- 2002/7: Extensions, new functions and structure
- 2007: Third generation: Java-based ToolBus

1992


Graphical Objects
Structure & text editor
Other parts
Emacs
User-interface
Structure editor
Other parts
Old
New

1993

- Difficult synchronization and communication problems problems start to appear
- PSF specification of communication; simulation reveals several deadlocks
- Problems with this specification:
  - complex (> 20 pages) and ad hoc
  - difficult to extend
  - cannot be used to directly coordinate the components

1993/1994

- Idea of a “ToolBus” as general communication structure appeared
- First design and implementation
- Several experiments
  - Feature interaction in telephone switches (RUU/PTT)
  - Traffic control (Nederland Haarlem/UvA/CWI/RUU)
  - Management of complex bus stations (idem)
  - Definition of user interfaces (UvA)

1994/1995

- Fall 1994: redesign based on this experience
- Spring 1995: design and implementation of Discrete Time ToolBus completed
- First experiments to prototype parts of the Meta-Environment started

More recently ...

- In 2001 a new implementation of the Meta-Environment based on the ToolBus was completed
- In 2007 we have completed a new generation ToolBus (Java-based) that is used by the Meta-Environment
- The ToolBus can be seen as a Service-oriented Architecture (SOA) *avant la lettre* ...

Structuring and Composition of Software

• Structured programming	*Statements*
• Functions, procedures & libraries	*Procedures*
• Object-oriented programming & Modules • Unix pipes • DCOM	*Modules*
• Coordination languages & SOA	*System*

Service-oriented Architecture (SOA)

- Loose coupling
- Service contract
- Autonomy
- Abstraction
- Reusability
- Composability
- Statelessness
- Discoverability
- Message exchange patterns
- Coordination
- Atomic transactions

ToolBus requirements

- Flexible interconnection architecture for software components
- Good control over communication
- Relatively simple descriptions
- Uniform data exchange format
- Multi-lingual: C, Java, Perl, ASF+SDF, ...
- Potential for verification
- Use existing concurrency theory: Process Algebra

Process Algebra

- A theoretical framework to describe process behaviour
- Consists of
  - Constants: deadlock (δ), silent step (τ)
  - Atomic actions: a, b, c, ...
  - Processes x, y, z, ... built with the operators:
    - sequential compositions: .
    - non-deterministic choice: +
    - parallell composition: ||

Basic Process Algebra (BPA)

The basic axioms for choice (+) and sequential composition (.):

A1. $x + y = y + x$
A2. $(x + y) + z = x + (y + z)$
A3. $x + x = x$
A4. $(x + y) \cdot z = x \cdot z + y \cdot z$
A5. $(x \cdot y) \; z = x \; \cdot y \cdot z$

Axioms for deadlock:

A6. $x + \delta = x$
A7. $\delta \cdot x = \delta$

Merge (||)

Use the auxiliary operator left merge (||_):

M1. $x \,||\, y = x||\_\ y + y\ ||\_\ x$
M2. $a\ ||\_\ x = a\ .\ x$
M3. $a\ .\ x\ ||\_\ y = a\ .\ (x\ ||\ y)$
M4. $(x + y)\ ||\_\ z = x\ ||\_\ z + y\ ||\_\ z$

Examples:

$a\ ||\ b = a\ ||\_\ b + b\ ||\_\ a = a\ .b + b\ .\ a$

$a\ .b\ ||\ c = a\ .b\ ||\_\ c + c\ ||\_\ a\ .\ b =$

$a\ .\ (b||c) + c.a.b = a\ .\ (\ b.c + c.b) + c.a.b$

Process Algebra versus ToolBus

- Process Algebra can be used to describe all (possibly infinite) behaviours of a collection of parallel processes
- This behaviour has the form of a process tree still containing all possible choices
- Properties of the parallel processes can be verified by verifying this behaviour description, e.g.
  - absence of deadlock

Process Algebra versus ToolBus

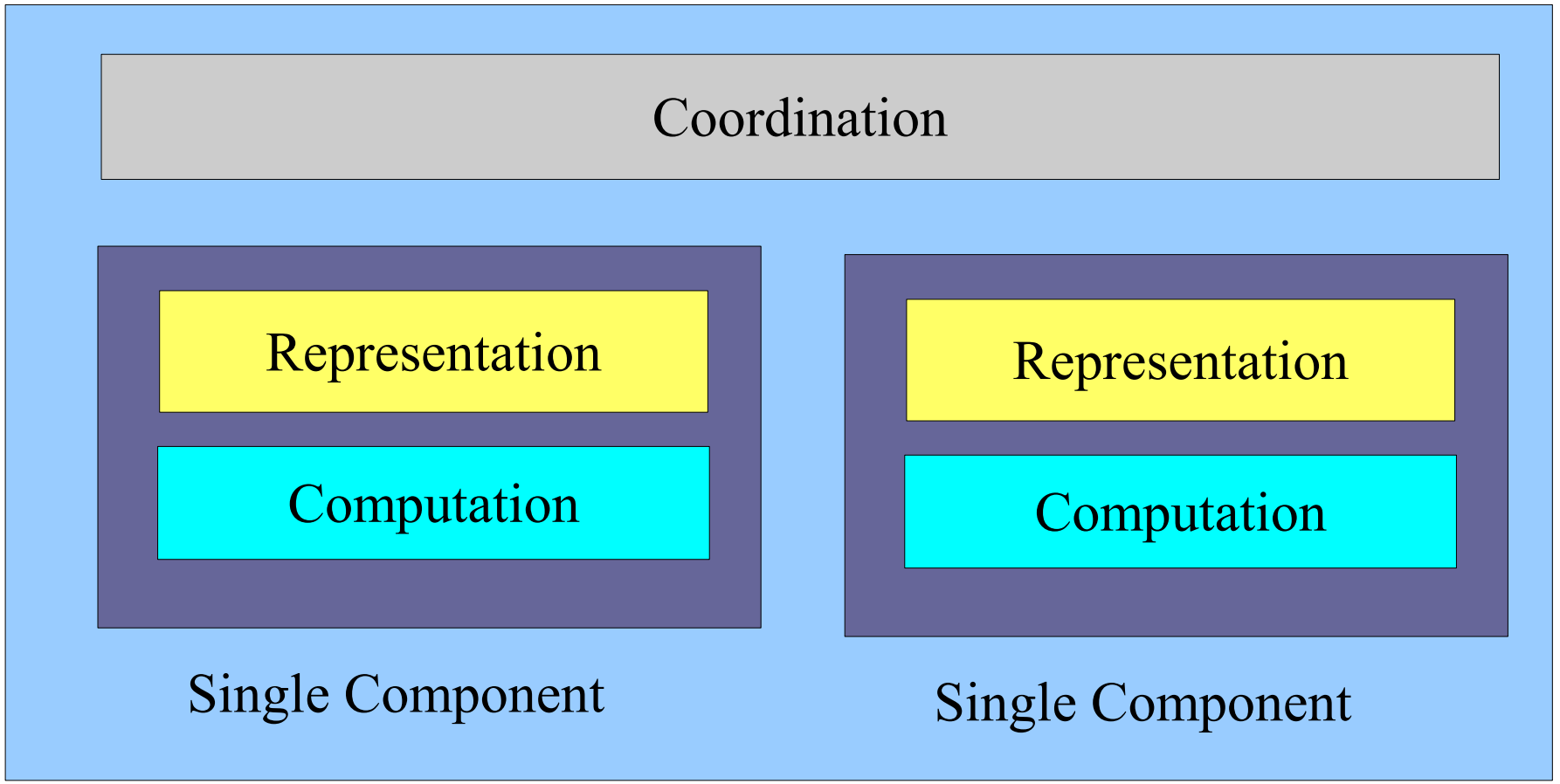
- Atomic actions may be enabled/disabled as a result of conditions or time constraints
- The ToolBus executes a process expression but randomly selects one of the enabled arguments of a choice operator
- The steps taking by the ToolBus are thus just one possible series of steps that is contained in the complete behaviour of the process expression:
  - a || b executes as a . b or as b .a (and not both!)

Coordination, Representation & Computation

- Coordination: the way in which program and system parts interact (procedure calls, RMI, ...)
- Representation: language and machine neutral data exchanged between components
- Computation: program code that carries out a specialized task

A rigorous separation of coordination from computation is the key to flexible and reusable systems

Architectural Layers



Cooperating Components

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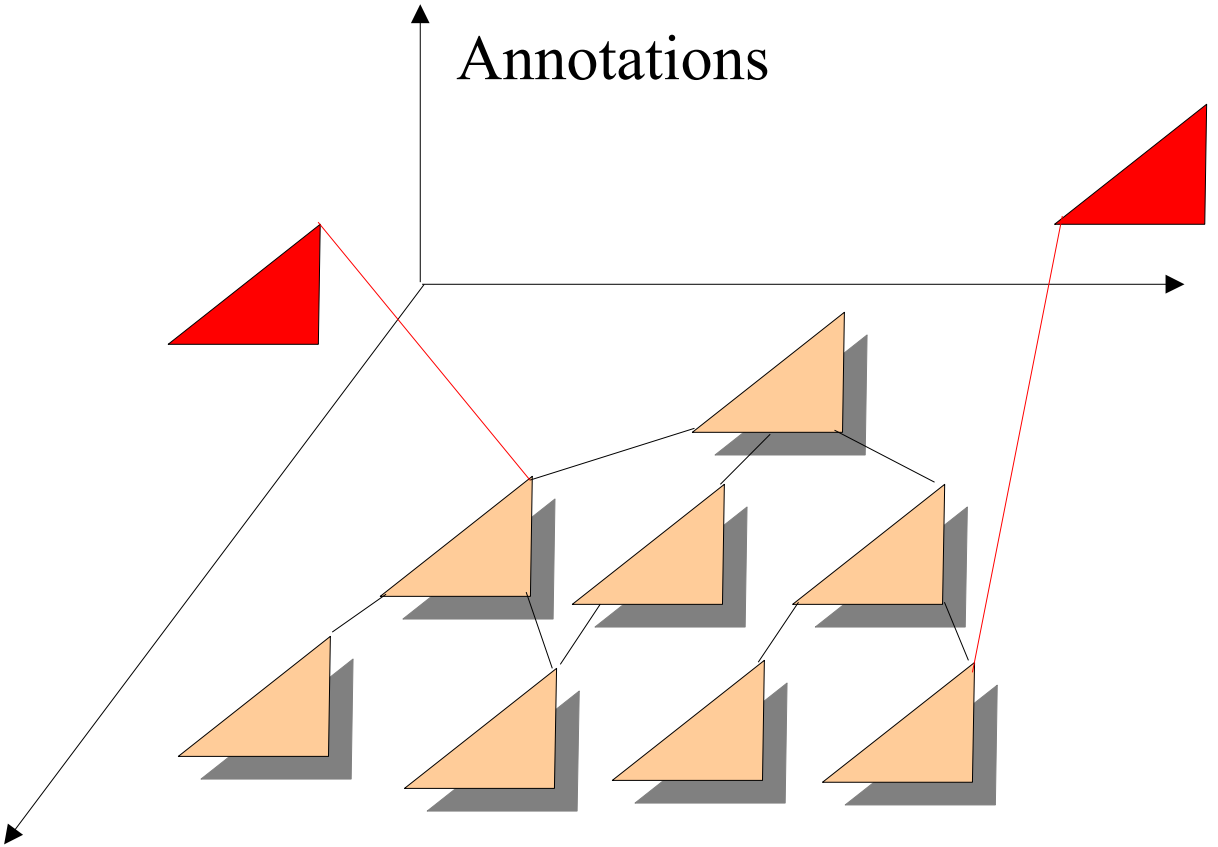
Why not using XML as terms?

- Has been tried in various language processing projects
- XML is too verbose to represent parse trees of large (> 100 KLOC) programs
- XML does not provided sharing
- For discussion see: M.G.J. van Brand and P. Klint, ATerms for manipulation and exchange of structured data: It's all about sharing, *Information and Software Technology*, **49**(1), 2007, 55-64.

Generic Representation
Annotated Terms (ATerms)

- Applicative, prefix terms
- Maximal subterm sharing ($\Rightarrow$ DAG)
  - cheap equality test, efficient rewriting
  - automatic generational garbage collection
- Annotations (text coordinates, dataflow info, ...)
- Very concise, binary, sharing preserving encoding
- Language & machine independent exchange format

ATerms
Term and Annotations



A term is ...

- a Boolean, integer, real or string
  - true, 37, 3.14e-12, "rose"
- a value occurrence of a variable
  - X, InitialAmount, Highest-bid
- a result occurrence of a variable
  - X?, InitialAmount?

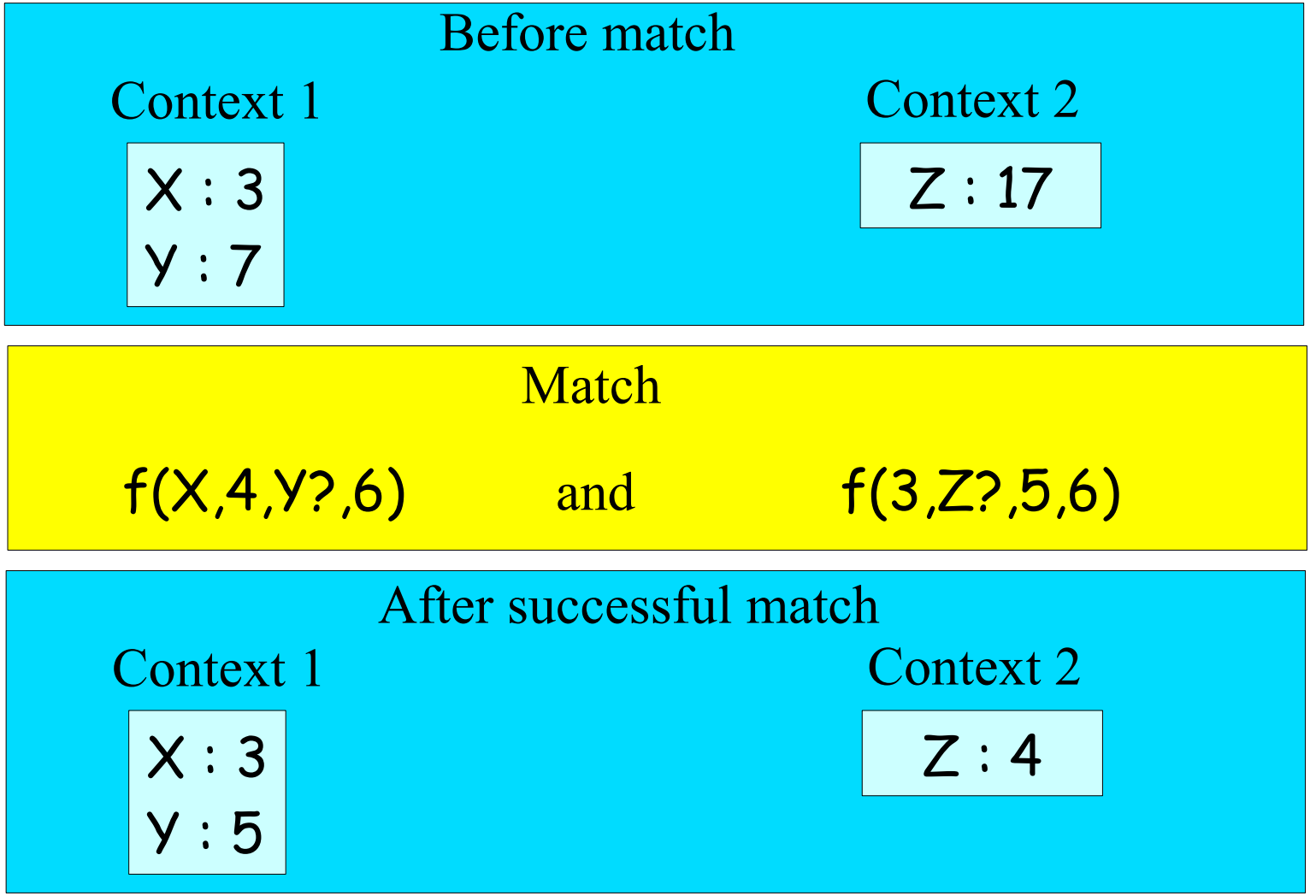
A term is ...

- a single identifier
  - f, pair, zero
- a function application
  - pair("rose", address("Street", 12345))
- a list
  - [a, b, c], [a, 1.25, "last"], [[a, 1], [b, 2]]
- a placeholder
  - <int>, add(<int>,<int>)

Matching of terms

- Term matching is used to
  - determine which actions can communicate
  - to transfer data between sender and receiver
- Intuition:
  - terms match if the are structurally identical
  - value occurrence: use variable's value
  - result occurrence: assign matched subterm to variable (only if overall match succeeds!)

Example of term matching



Types

- The ToolBus uses its own type system
  - static checks & automatic generation of interface code
- bool, int, real, str
- list: list with arbitrary elements
- list(*Type*): list with *Type* elements
  - list(int)
- *term*: arbitrary term

Types

- *Id*: all terms with function symbol *Id* (allows partial type declarations)
  - `f` accepts `f`, `f(1)`, `f("abc",3)`, ...
- $Id(T_1, ..., T_n)$
  - `f(int, str)` accepts `f(3,"abc")` but not `f(3)`
- $[T_1, ..., T_n]$: list of elements with given types
  - `[int, str]` accepts `[1,"abc"]` but not `[1,2,3]`

Types

- All variables have types
- Types are checked statically when possible
- Types play a role during matching:
  - `I` is `int` variable, `S` is `str` variable, `T` is term variable
  - match `f(13)` and `f(I?)` succeeds
  - match `f(13)` and `f(S?)` fails
  - match `f(13)` and `f(T?)` succeeds

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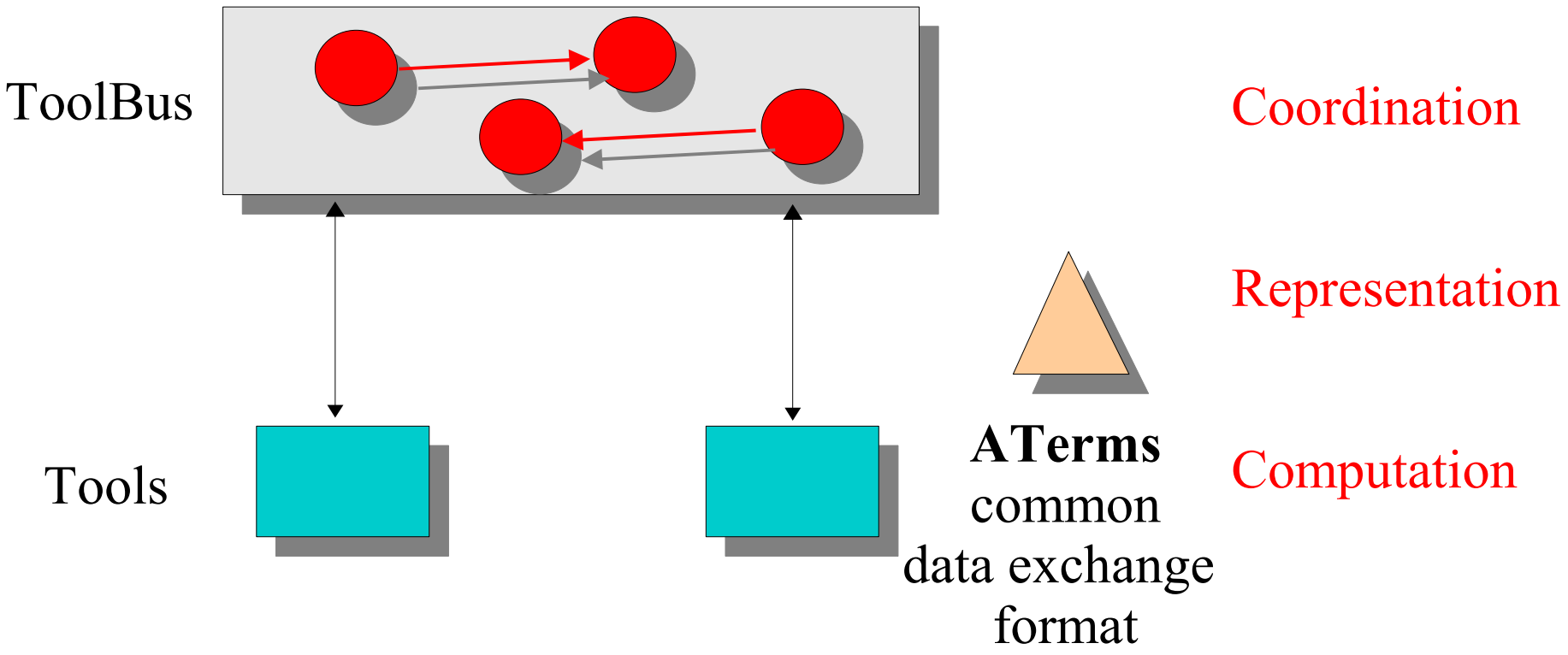
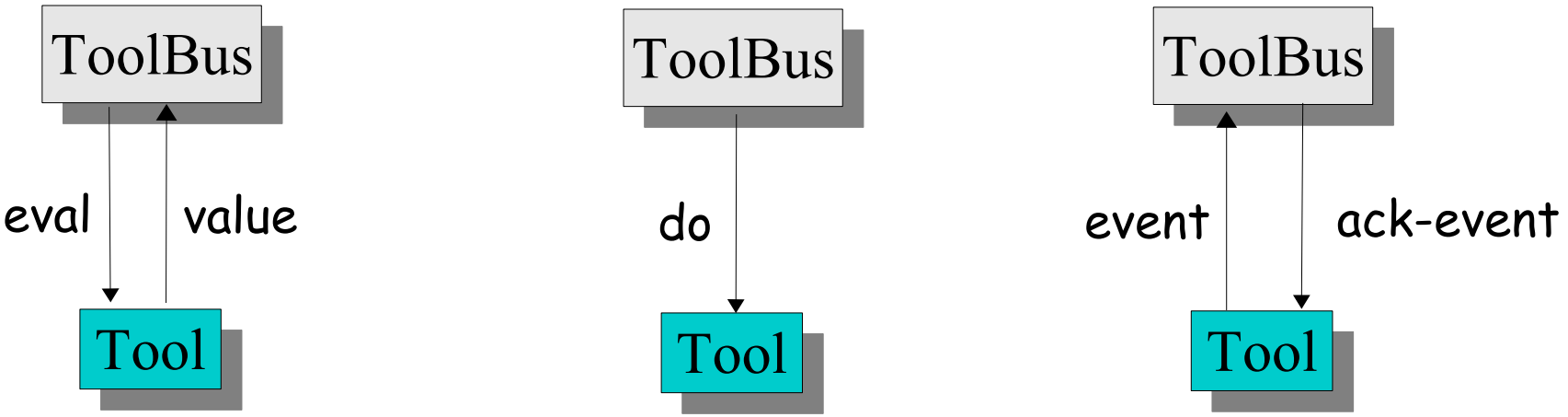
The ToolBus architecture

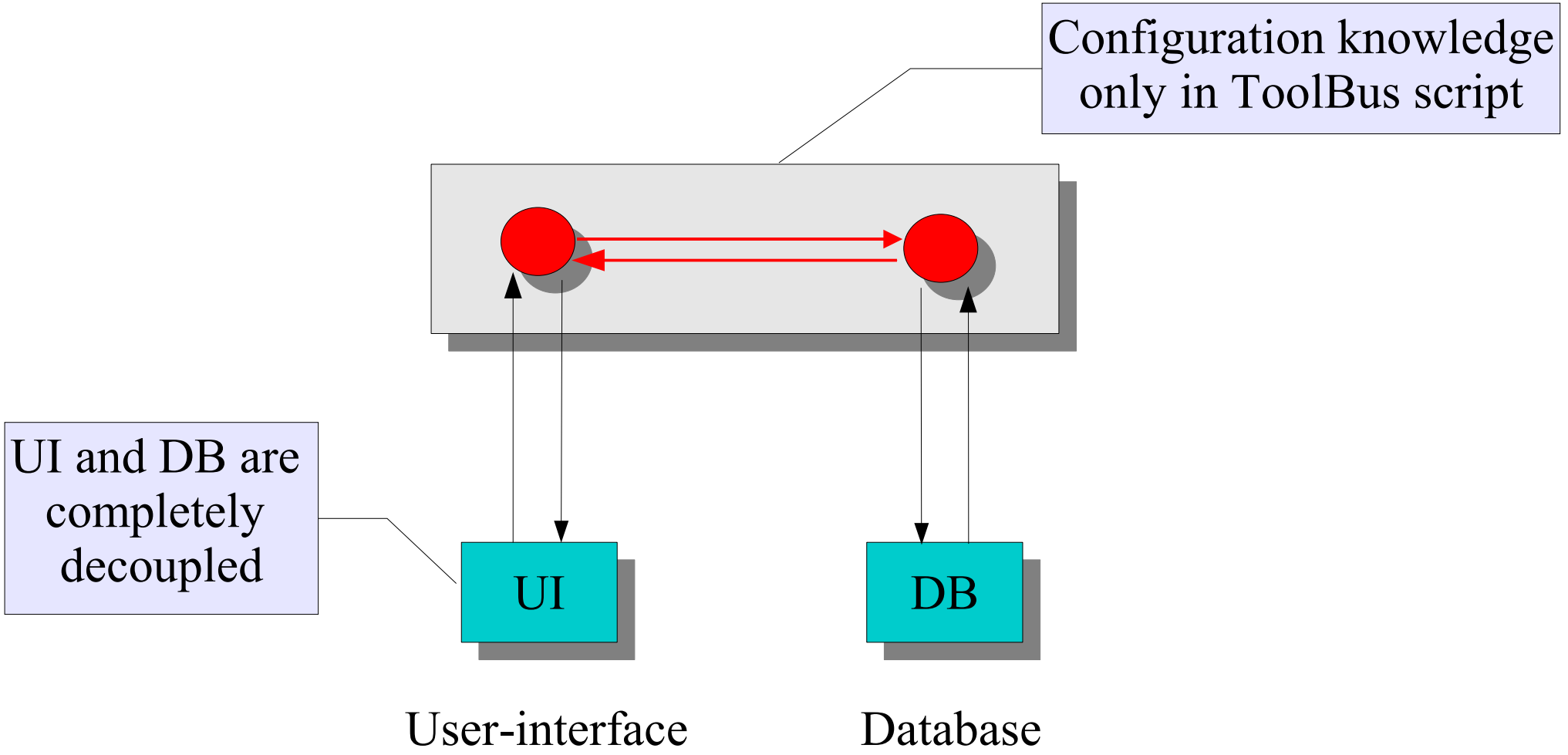


The ToolBus architecture

- Processes inside the ToolBus can communicate with each other
- Tools can not communicate with each other
- Tools can communicate using a fixed protocol:



A typical scenario



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ToolBus scripts: processes

- The ToolBus: a parallel composition of processes
- Private variables per process
- $P_1 + P_2$ $P_1 . P_2$ $P_1 || P_2$ $P_1 * P_2$
- :=, if then else
- All data are terms that can be matched
- A limited set of built-in operations on terms
- No other support for datatypes

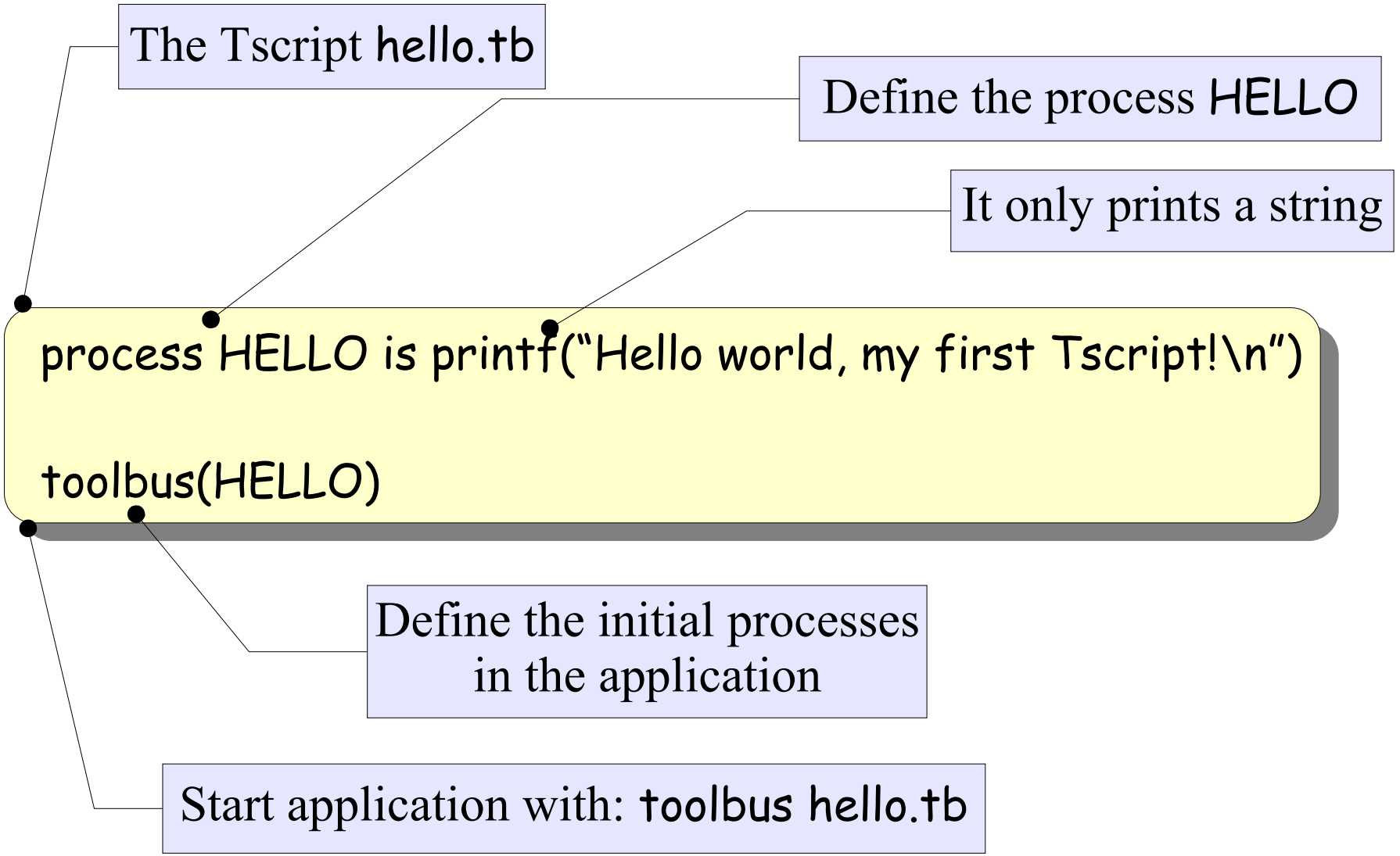
ToolBus scripts: processes

- Send, receive message (handshaking)
- Send/receive notes (broadcasting)
- Subscription to notes
- Dynamic process creation
- Absolute/relative delay, timeout

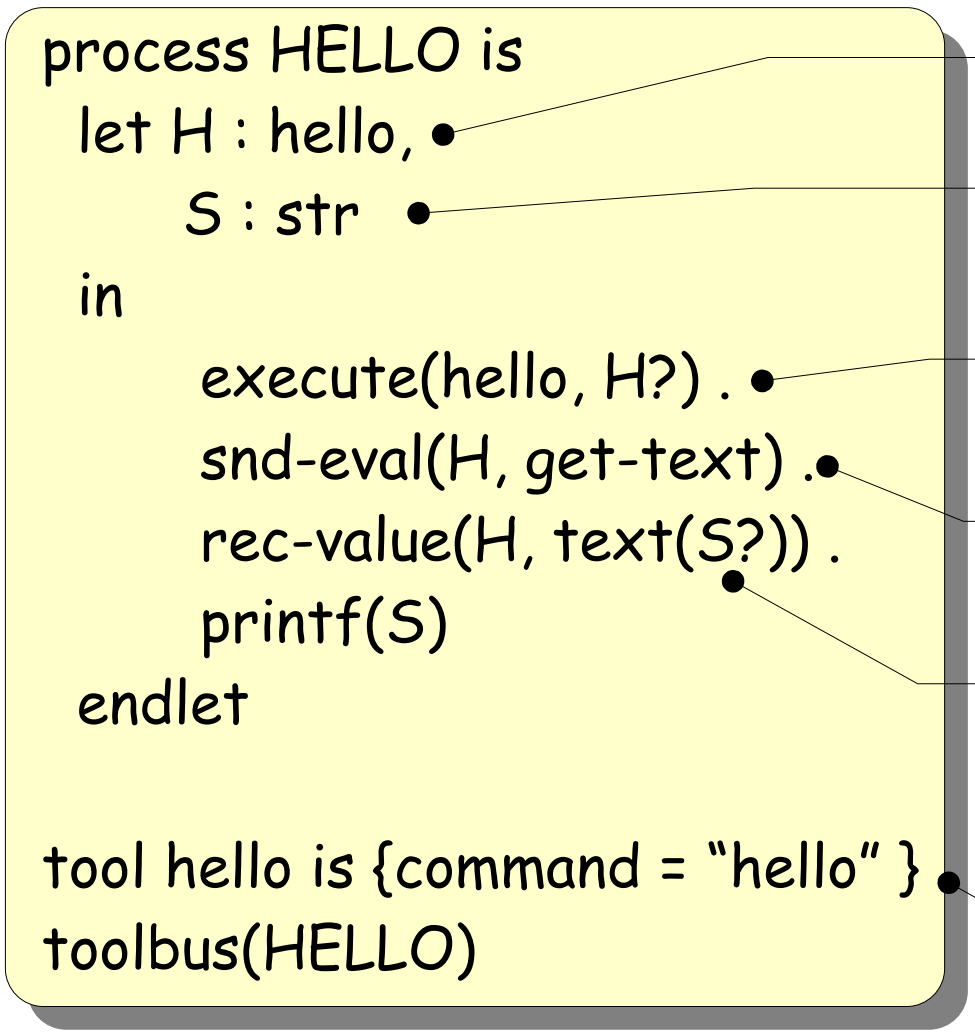
ToolBus scripts: tools

- Execute/terminate tools
- Connect/disconnect tools
- Communication between process and tool is synchronous
- Process can send evaluation request to tool (which returns a value later on)
- Tool can generate events to be handled by the ToolBus

Hello World


The Tscript hello.tb
Define the process HELLO
It only prints a string
process HELLO is printf("Hello world, my first Tscript!\n")
toolbus(HELLO)
Define the initial processes in the application
Start application with: toolbus hello.tb

Hello World: string generated by tool



H will represent the tool

S is a string variable

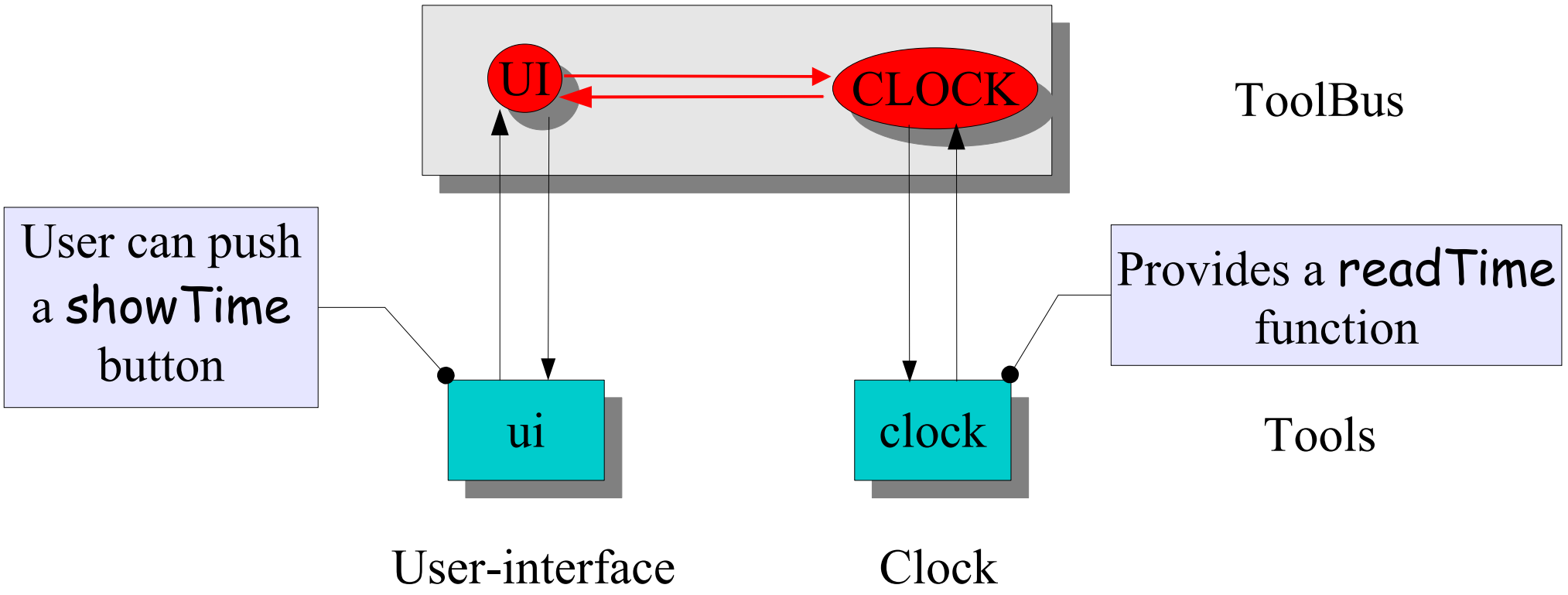
Execute hello,
H gets a tool id as value

Request a text from hello tool

Receive it,
S gets the value assigned

Definition of hello tool:
may be written in any language

Simple clock with user-interface



Simple clock with user-interface

process CLOCK is process-expression-1
tool clock is tool-definition-1

process UI is process-expression-2
tool ui is tool-definition-2

toolbus(CLOCK, UI)

Clock

```
process CLOCK is
    let Tid : clock, T : str
    in
        execute(clock, Tid?).
        (
            rec-msg(showTime) .
            snd-eval(Tid, readTime) .
             rec-value(Tid, time(T?)) .
             snd-msg(showTime, T)
          ) * delta
    endlet
```

Receive a message from another process

Get time from clock tool

Reply to the message

(...) * delta is an endless loop

```
tool clock is { command = "clock" }
```

User-interface

```
process UI is
  let Tid : ui, T : str
  in
       execute(ui, Tid?) .
       ( rec-event(Tid, button(showTime)) .
         snd-msg(showTime) .
         rec-msg(showTime, T?) .
         snd-do(Tid, displayTime(T)) .
         snd-ack-event(Tid, button(showTime))
       ) * delta
 endlet
```

Receive event from ui tool

Get the time

Display it in ui tool

Processing of the event complete: send acknowledgment

```
tool ui is { command = "wish-adapter -script ui.tcl" }
```

Tscripts: in more detail

- Process communication: messages & notes
- Composite processes
- Expressions & built-in functions
- Time primitives
- Tools

Process communication: messages

- Messages used for synchronous, two-party communication between processes
- `snd-msg` and `rec-msg` synchronize sender/receiver
- Communication is possible if the arguments match
- There is two-way data transfer between sender and receiver (using result variables)

Process communication: notes

- Notes used for asynchronous, broadcasting communication between processes
- Each process must subscribe to the notes it wants to receive
- Each process has a private note queue on which `snd-note`, `rec-note` and `no-note` operate

Process communication: notes

- subscribe to notes of a given form
  - subscribe(compute(<str>,<int>))
- unsubscribe from certain notes
- snd-note to all subscribers
  - snd-note(compute(E,V))
- rec-note: receive a note of a given form
- no-note received of given form

Composite process expressions

- One of the atomic processes mentioned above
- delta (deadlock), tau (silent step)
- P_1 + P_2: choice (non-deterministic)
- P_1. P_2: sequential composition
- P_1 || P_2: parallel composition
- P_1 * P_2: repetition

Composite process expressions

- P(T_1, T_2, ...): a named process (with optional parameters) will be replaced by its definition
- create(P(T_1, T_2, ...), Pid?): dynamic process creation
- V := Expr: evaluate Expr and assign result to V
- if Expr then P_1 else P_2 fi
- if Expr then P_1 fi = if Expr then P_1 else delta fi

Expressions

- An expression is evaluated in the current environment of the process in which it occurs
- Constants evaluate to themselves: `a`
- Variables evaluate to their current values
- Lists evaluate to a list of their evaluated elements
- Some function symbols have a built-in meaning

Built-in functions

- Booleans: not, and, or
- Integers: add, sub, mul, mod, less, less-equal, greater, greater-equal
- Lists: first, next, get, put, join, member, subset, diff, inter, size
- Miscellaneous: equal, not-equal, process-id, process-name, current-time, quote

Time primitives

- A (relative or absolute) delay or time out may be associated with each atomic process
- Relative time: delay(Expr) or timeout(Expr)
- Absolute time: abs-delay(y, mon, d, h, min, s) or abs-timeout(y, mon, d, h, min, s)
- Example:
  - printf("expired") delay(10)
  - printf("Renew account") abs-timeout(2008,4,1,12,0,0)

Process definitions

- Process definition: process *Pname Formals* is *P*
- *Formals* are optional and contain a list of formal parameter names
  - process MakeWave(N : int) is ...
- All variables (including formals) must be declared and have a type
- let *VarDecls* in *P* endlet introduces variables:
  - let E : str, V : int in ... endlet

Tools

- Tools have to be executed or connected before they can be used
- Requires a tool definition: `tool ui is { ... }`
- Introduces a new type, e.g. `ui`
- Execute a tool: `execute(ui, Uid?)`
- Receive connection request: `rec-connect(ui, Uid?)`
- Tool identification is assigned to `Uid` (of type `uid`)

Tools

- snd-terminate: terminate an executing tool
  - snd-terminate(Tid)
- rec-disconnect: receive disconnection request from tool
  - rec-disconnect(Uid)
- shutdown: terminate the whole ToolBus
  - shutdown("Auction ends")

Tools

- snd-eval, rec-value: request tool to evaluate a term, and receive the resulting value from tool
  - initiative: ToolBus
- snd-do: request tool to perform some action, there is no reply
  - initiative: ToolBus
- rec-event, snd-ack-event: receive event from tool, acknowledge it after appropriate processing
  - initiative: tool

Tscripts

- A Tscripts consists of
  - a list of process and tool definitions
  - a single ToolBus configuration
- A ToolBus configuration describes the initial set of active processes in the ToolBus:
  - `toolbus(`$Pname_1$, ..., $Pname_n$`)`
  - Eache *Pname* is optionally followed by parameters

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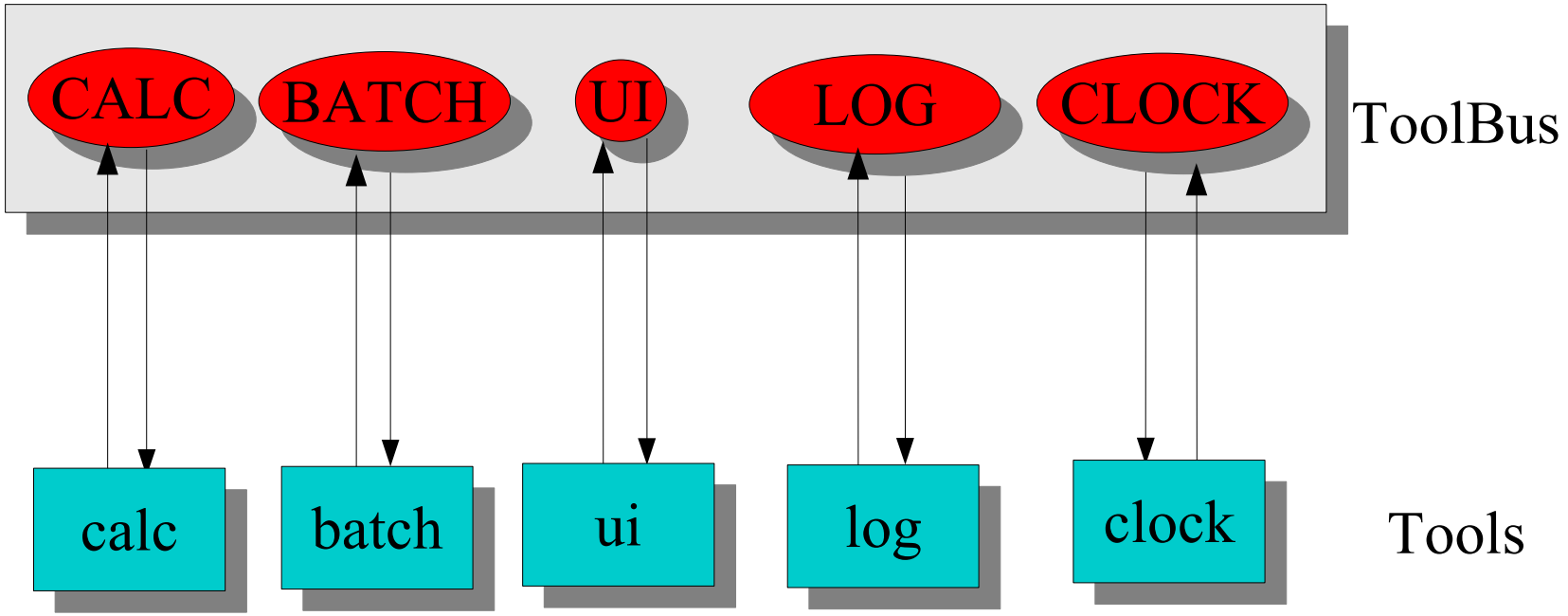
Example: calculator



Example: calculator

- CALC: the calculation process
- BATCH: reads expressions from file, calculates their value, writes result back to file
- UI: the user-interface
- LOG maintains a log of all calculations
- CLOCK provides current time

Process CALC

```
process CALC is
    let Tid : calc, E : str, V : term
    in
        execute(calc, Tid?).
         (
            rec-msg(compute, E?) .
            snd-eval(Tid, expr(E)) . rec-value(Tid, val(V?)) .
             snd-msg(compute, E, V) . snd-note(compute(E, V))
          )* delta
    endlet

tool calc is { command = "calc"}
```

Receive compute message

Let calc do the computation

Note for the logger

Reply to compute message

Process BATCH

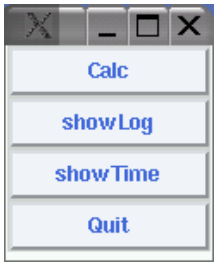
```
process BATCH is
    let Tid : batch, E : str, V : int
    in
        execute(batch, Tid?).
        (
            snd-eval(Tid, fromFile) . rec-value(Tid, expr(E?)) .
            snd-msg(compute, E) . rec-msg(compute, E, V?) .
            snd-do(Tid, toFile(E, V))
         ) * delta
    endlet

tool batch is {command = "batch"}
```

Get an expression from batch tool

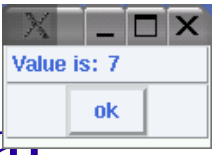
Evaluate expression

Value back to batch tool

User-interface



- When the user presses Calc, a dialog window appears to enter an expression
- The result is diplayed in a separate window
- Pressing showLog display all calculations so far
- Pressing showTime displays the current time
- Pressing Quit ends the application



User-interface: process UI

```
process UI is
   let Tid : ui
   in
         execute(ui, Tid?) .
         ( CALC-BUTTON(Tid) + LOG-BUTTON(Tid))* delta
          ||
          TIME-BUTTON(Tid) * delta
          ||
          QUIT-BUTTON(Tid)
   endlet

tool ui is { command = wish-adapter -script calc.tcl" }
```

Calc and Log button are exclusive

Time and Quit button are independent

User-interface: CALC-BUTTON

```
process CALC-BUTTON(Tid : ui) is
    let N : int, E : str, V : term
    in
          rec-event(Tid, N?, button(calc)) .
          snd-eval(Tid, get-expr-dialog) .
          (  rec-value(Tid, cancel)
          +  rec-value(Tid, expr(E?)) .
             snd-msg(compute, E) .
             rec-msg(compute, E, V?) .
              snd-do(Tid, display-value(V))
          ) . snd-ack-event(Tid, N)
    endlet
```

Calc button is pressed

Ask for an expression

Get cancel or an expression

Compute expression and display its value

Acknowledge the button event

User-interface: LOG-BUTTON

```
process LOG-BUTTON(Tid : ui) is
    let N : int, L : term
    in
        rec-event(Tid, N?, button(showLog)) .
        snd-msg(showLog) .
        rec-msg(showLog, L?) .
        snd-do(Tid, display-log(L)) .
        snd-ack-event(Tid, N)
    endlet
```

User-interface: TIME-BUTTON

```
process TIME-BUTTON(Tid : ui) is
    let N : int, T : str
    in     rec-event(Tid, N?, button(showTime)) .
           snd-msg(showTime) .
           rec-msg(showTime, T?) .
           snd-do(Tid, display-time(T)) .
           snd-ack-event(Tid, N)
    endlet
```

```
process QUIT-BUTTON(Tid : ui) is
       rec-event(Tid, button(quit)) .
       shutdown("End of calc demo")
```

Process LOG

```
process LOG is
   let Tid : log, E : str, V : term, L : term
   in   subscribe(compute(<str>, <term>)) .
         execute(log, Tid?).
            (      rec-note(compute(E?, V?)) .
                   snd-do(Tid, writeLog(E, V))
            +
                   rec-msg(showLog) .
                   snd-eval(Tid, readLog) .
                   rec-value(Tid, history(L?)) .
                   snd-msg(showLog, history(L))
            ) * delta
   endlet
```

Log all calculations

Show the log of calculations

Process LOG1

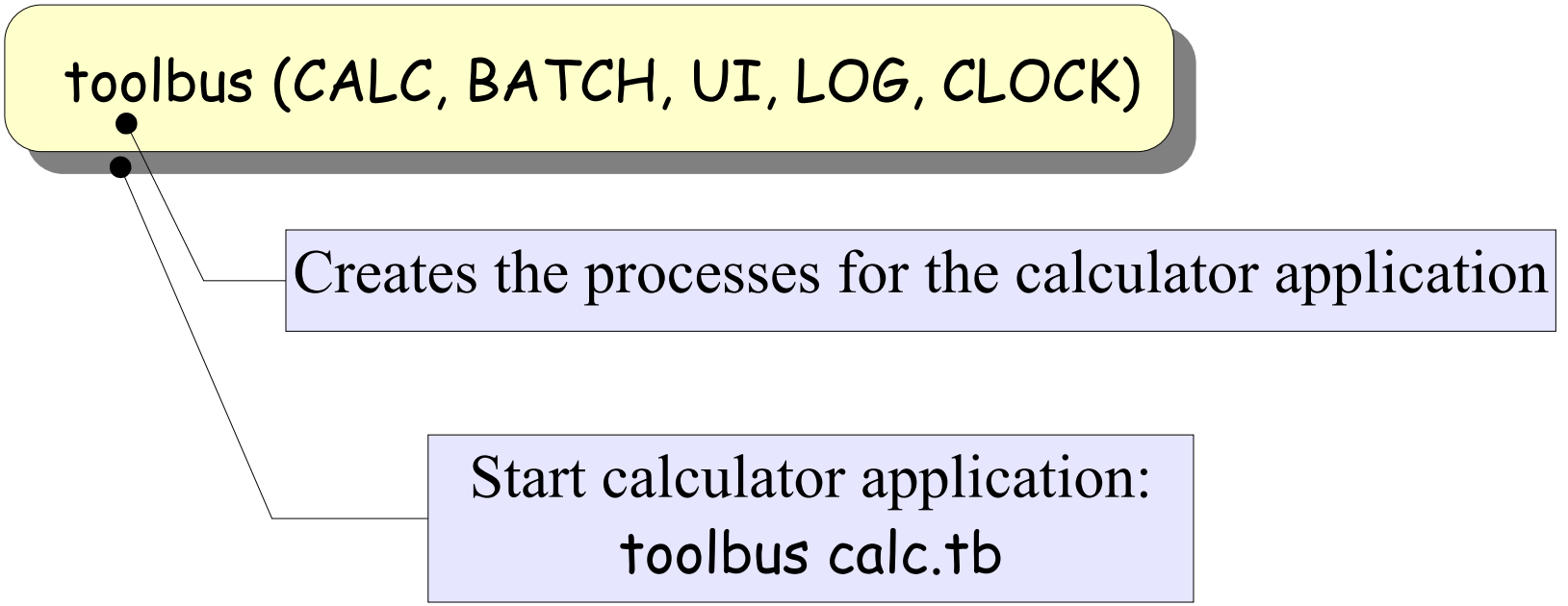
```
process LOG1 is
   let TheLog : list, E : str, V : term
   in     subscribe(compute(<str>, <term>)) .
          TheLog := [] .
             (      rec-note(compute(E?, V?)) .
                    TheLog := join(TheLog, [[E, V]])
              +
                    rec-msg(showLog) .
                    snd-msg(showLog, TheLog)
             ) * delta
   endlet
```

Alternative definition of logger: maintain the log in a list

Process CLOCK

```
process CLOCK is
   let Tid : clock, T : str
   in
         execute(clock, Tid?).
          (     rec-msg(showTime) .
                snd-eval(Tid, readTime) .
                rec-value(Tid, time(T?)) .
                snd-msg(showTime, T)
           ) * delta
   endlet
```

ToolBus Configuration



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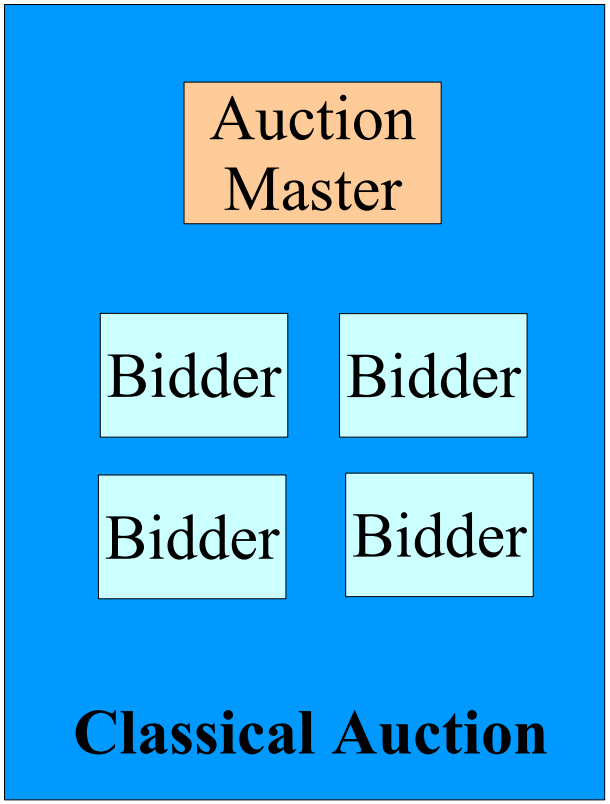
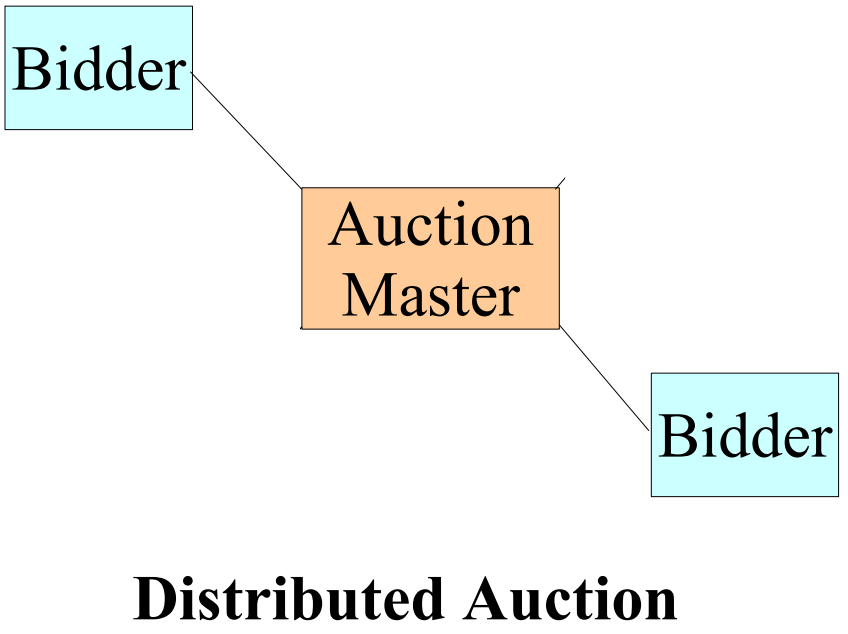
Example: distributed auction

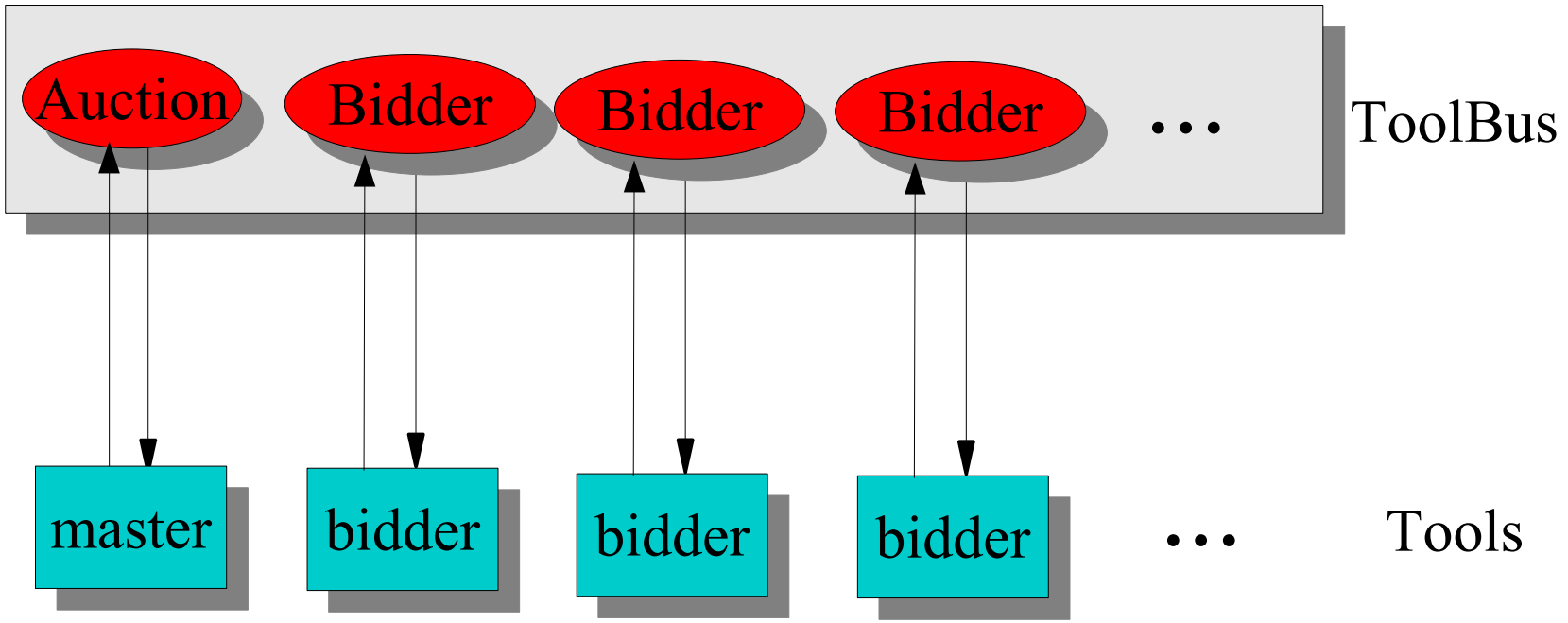




Example: distributed auction

- How are bids synchronized?
- How to inform bidders about higher bids?
- How to decide when the bidding is over and the item is sold?
- Bidders may come and go during the auction

Example: distributed auction



Example: distributed auction

- The Auction process
  - executes master tool: user-interface of auction master
  - connection/disconnection of new bidders
  - introduces new items for sale (at the initiative of the auction master)
  - controls the bidding provess via OneSale
- A Bidder process is created for each new bidder

Process Auction

```
process Auction is
  let Mid : master, Bid : bidder
  in
      execute(master, Mid?) .
      ( ConnectBidder(Mid, Bid?)
      +
        OneSale(Mid)
      ) *
      rec-event(Mid, quit) .
      shutdown("Auction is closed")
  endlet
```

Execute the **master** tool

Repeat:
- add new bidder between sales,

or
- perform one sale

Until:
- auction master quits

Close the auction application

```
tool master is { command = "wish-adapter -script master.tcl" }
```

Process ConnectBidder

```
process ConnectBidder(Mid : master, Bid : bidder?)
is
  let Pid : int, Name : str
  in
     rec-connect(Bid?) .
     create(Bidder(Bid), Pid?) .
     snd-eval(Bid, get-name) .
     rec-value(Bid, name(Name?)) .
     snd-do(Mid, new-bidder(Bid, Name))
  endlet
```

Receive a connection request from a new bidder tool

Create a new Bidder process

Ask bidder for its name

Send name to master tool

Process OneSale

```
process OneSale(Mid : master) is
  let Descr : str,          %% Description of current item for sale
      InAmount : int,       %% Initial amount for item
      Amount : int,         %% Current amount
      HighestBid : int,     %% Highest bid so far
      Final : bool,         %% Did we already issue a final call for bids?
      Sold : bool,          %% Is the item sold?
      Bid : bidder          %% New bidder tool connected during sale
  in rec-event(Mid, new-item(Descr?, InAmount?)) .
      HighestBid := InAmount .
      snd-note(new-item(Descr, InAmount)) .
      Final := false . Sold := false .
      ( ...
      ) * if Sold then snd-ack-event(Mid, new-item(Descr, InAmount)) fi
  endlet
```

Where the action is ...

Process OneSale

```
( if not(Sold) then ... fi
+ if not(or(Final, Sold)) then    ... fi
+ if and(Final, not(Sold)) then ... fi
+ ConnectBidder(Mid, Bid?) ...
) * if Sold then ... fi
```

Process OneSale

```
( if not(Sold) then
    rec-msg(bid(Bid?, Amount?)) .
    snd-do(Mid, new-bid(Bid, Amount)) .
    if less-equal(Amount, HighestBid) then
       snd-msg(Bid, rejected)
    else
       HighestBid := Amount .
       snd-msg(Bid, accepted) .
       snd-note(update-bid(Amount)) .
       snd-do(Mid, update-highest-bid(Bid, Amount)) .
       Final := false
    fi
  fi
+ if not(or(Final, Sold)) then    ... fi
+ if and(Final, not(Sold)) then ... fi
+ ConnectBidder(Mid, Bid?) ...
) * if Sold then ... fi
```

Receive a bid from a bidder

Inform auction master about it

Reject bid if it is too low

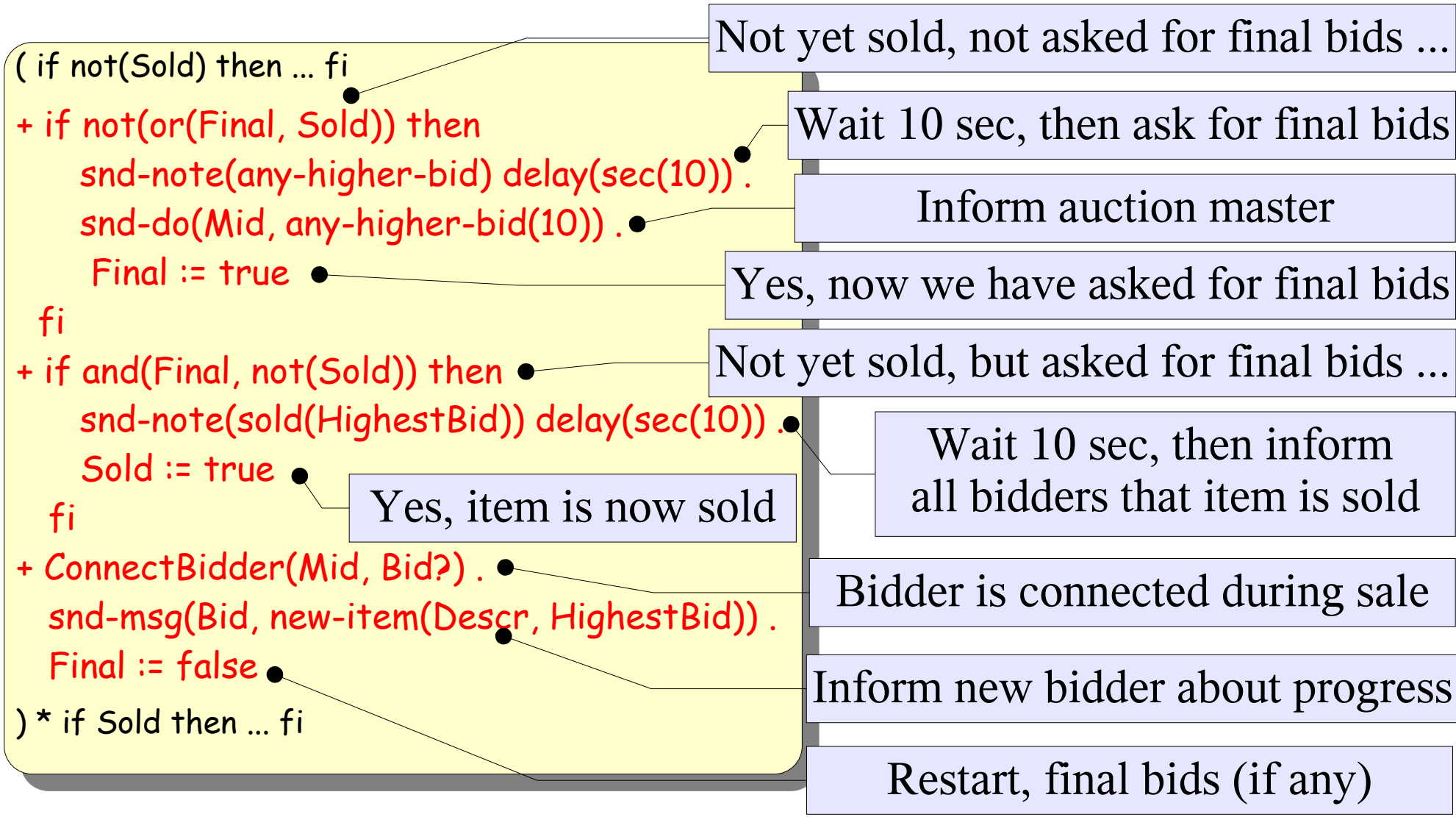
Remember as highest bid

Inform bidder: bid is accepted

Inform *all* bidders

Update auction master

Process OneSale



Process Bidder

```
process Bidder(Bid : bidder) is
  let Descr : str,  Amount : int,  Acceptance : term
  in
     subscribe(new-item(<str>, <int>)) . subscribe(update-bid(<int>)) .
     subscribe(sold(<int>)) . subscribe(any-higher-bid) .
     (  ...
     )
     * delta
  endlet
```

Process Bidder

Get info about item for sale after connection

```
( ( rec-msg(Bid, new-item(Descr?, Amount?))
  + rec-note(new-item(Descr?, Amount?))
  + rec-disconnect(Bid) . delta
  ) .
  snd-do(Bid, new-item(Descr, Amount)) .
  ( rec-event(Bid, bid(Amount?)) .
    snd-msg(bid(Bid, Amount)) . rec-msg(Bid, Acceptance?) .
    snd-do(Bid, accept(Acceptance)) . snd-ack-event(Bid, bid(Amount))
  + rec-note(update-bid(Amount?)) . snd-do(Bid, update-bid(Amount))
  + rec-note(any-higher-bid) . snd-do(Bid, any-higher-bid)
  + rec-disconnect(Bid) . delta
  ) *
  rec-note(sold(Amount?)) . snd-do(Bid, sold(Amount))
) *
delta
```

Same, but normal case

Disconnect between sales

Inform bidder tool

bidder comes with new bid

Inform bidder

Disconnect during sale

End of this sale sale

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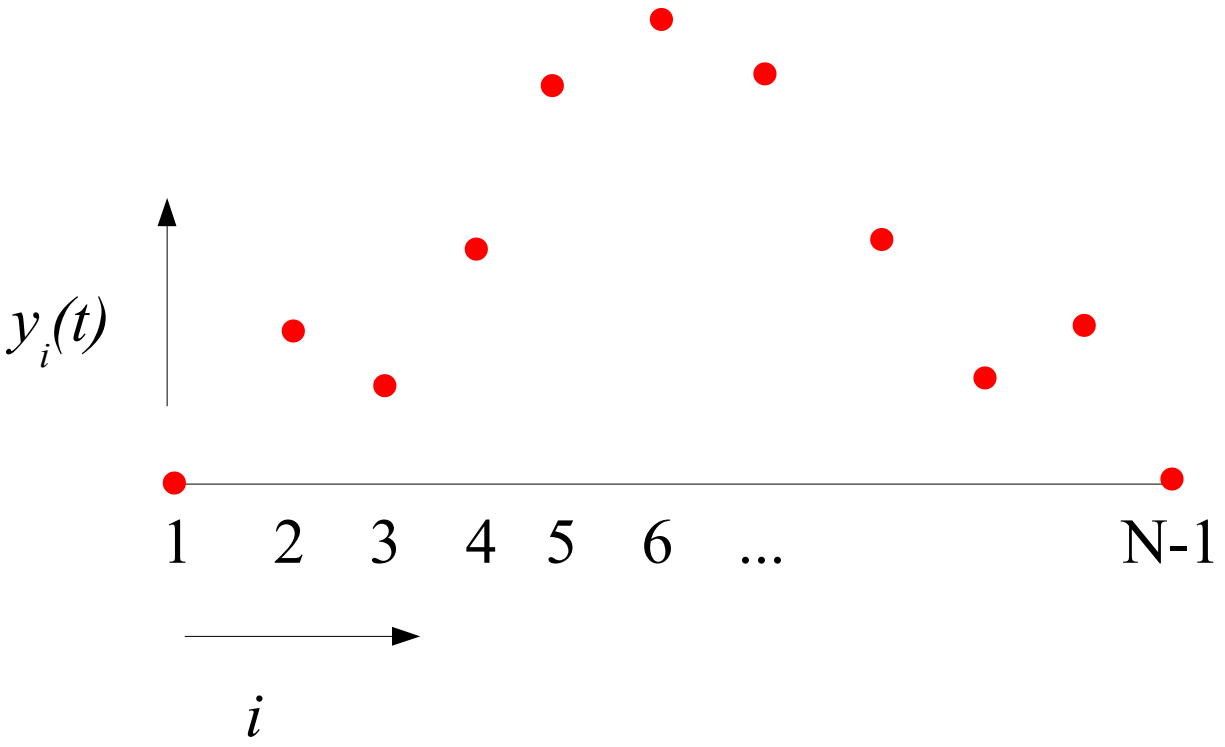
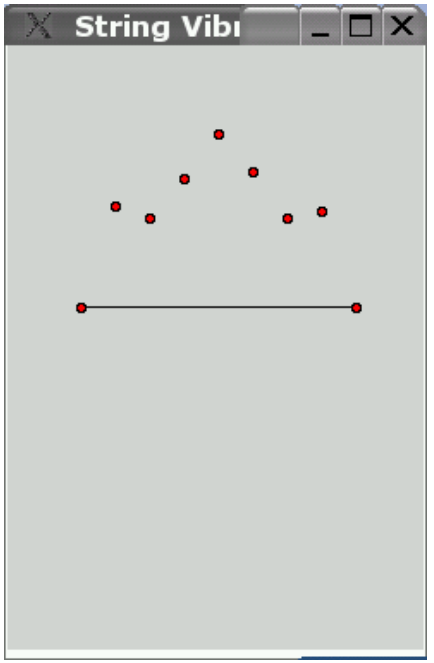
One-dimensional wave equation

Simulate a string attached at the two end points:





One-dimensional wave equation

Amplitude at point i at $t+\Delta t$ is given by:

$$y_i(t+\Delta t) = F(y_i(t), y_i(t-\Delta t), y_{i-1}(t), y_{i+1}(t))$$

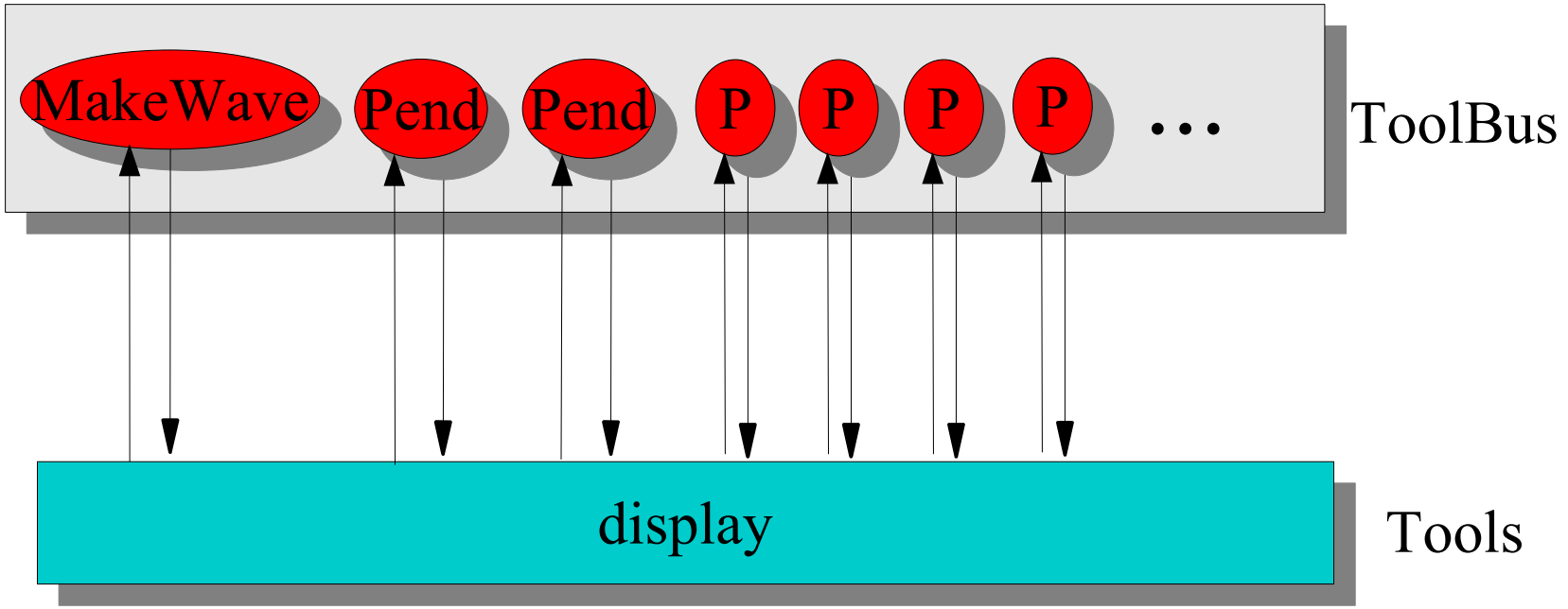
and

$$F(z_1,z_2,z_3,z_4) = 2z_1 - z_2 + (c\,\Delta t/\Delta x)^2\,(z_3 - 2z_1 + z_4)$$

Δx: the (small) interval between sampling points

c: constant representing the propagation velocity of the wave

Example: wave equation



One-dimensional wave equation

- Auxiliary process `F` computes function F
- Process `P` models a sampling point
- Process `Pend` models the end points
- Process `MakeWave` constructs *N* connected instances of `P` and two end points
- Tool `display` visualizes the simulation

Process F

Compute $F(z_1,z_2,z_3,z_4) = 2z_1 - z_2 + (c\ \Delta t/\Delta x)^2\ (z_3 - 2z_1 + z_4)$

```
process F(Z1 : real, Z2 : real, Z3 : real, Z4 : real, Res : real?) is
  let CdTdX2 : real
  in
    CdTdX2 := 0.01 .
    Res := radd(rsub(rmul(2.0, Z1), Z2),
               rmul(CdTdX2,
                  radd(rsub(Z3, rmul(2.0, Z1)), Z4)))
  endlet
```

Arbitrary value for $(c\ \Delta t/\Delta x)^2$

$2z_1 - z_2 +$

$(c\ \Delta t/\Delta x)^2 *$

$(z_3 - 2z_1 + z_4)$

Process P

```
process P(Tid : display, L : int, I : int, R : int, Dstart : real, Estart : real) is
  let AL : real, AR : real, D : real, D1 : real, E : real
  in
    D := Dstart . E := Estart .
    ( (  rec-msg(L, I, AL?)
      || rec-msg(R, I, AR?)
      || snd-msg(I, L, E)
      || snd-msg(I, R, E)
      || snd-do(Tid, update(I, E))
      ) .
      D1 := E .
      F(E, D, AL, AR, E?) .
      D := D1
    ) * delta
  endlet
```

L: left, I: this point, R: right

D, E: amplitutes of this point

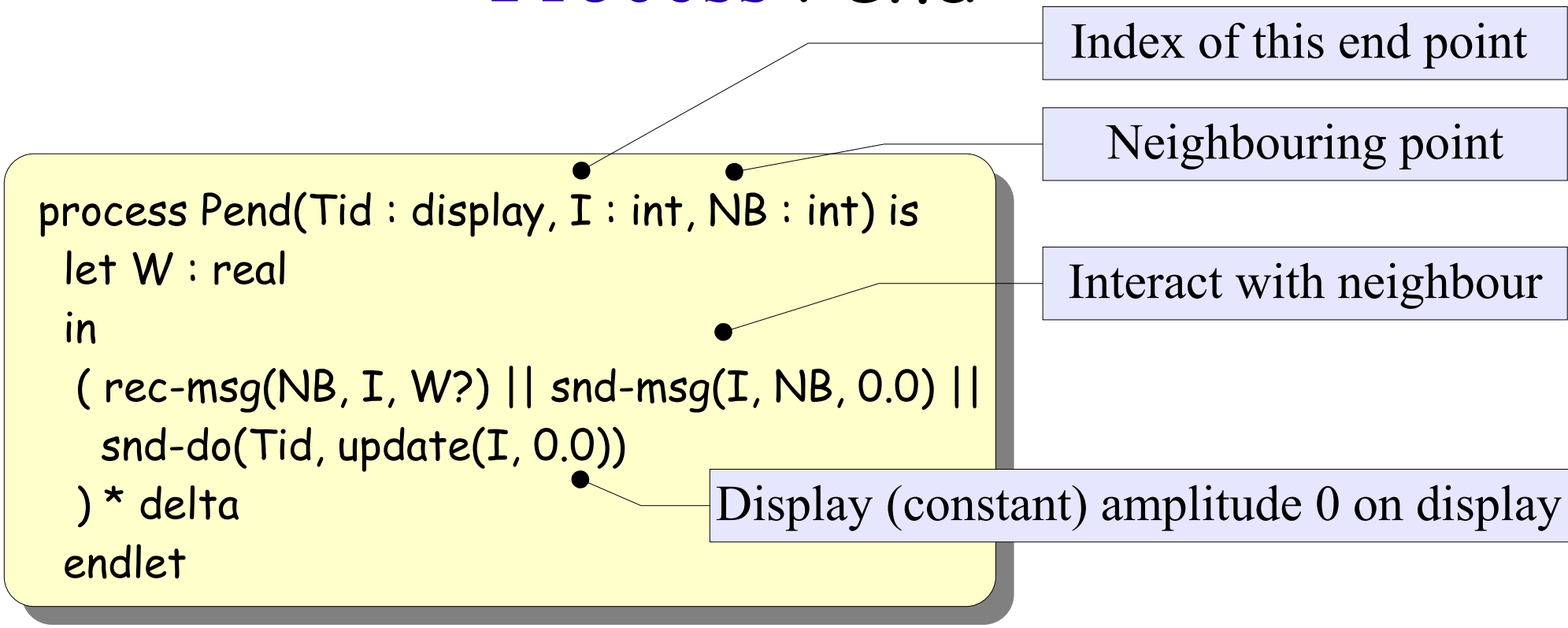
Receive amplitudes of neighbours

Send our amplitude to neighbours

Update our amplitude on display

Compute new versions of D and E

Process Pend



Process MakeWave

```
process MakeWave(N : int) is
  let Tid : display, Id : int, I : int, L : int, R : int
  in
    execute(display, Tid?) .
    snd-do(Tid, mk-wave(N)) .
    create(Pend(Tid, 0, 1), Id?).
    L := sub(N,1) .
    create(Pend(Tid, N, L), Id?) .
    I := 1 .
    if less(I, N) then
      L := sub(I, 1) . R := add(I, 1) .
      create(P(Tid, L, I, R, 1.0, 1.0), Id?) .
      I := add(I, 1)
    fi *
    shutdown("end") delay(sec(60))
  endlet
```

Execute display tool and initialize it

Create the two end points

Create the other points

Shutdown after one minute

Tool definition and ToolBus configuration

```
tool display is { command = "wish-adapter -script ui-wave.tcl"}

toolbus(MakeWave(8))
```

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Requirements ATerms

- Open: independent of hw/sw platform
- Simple: a small API
- Efficient: fast reading and writing
- Concise: small memory usage
- Language-independent
- Annotations: applications can transparantly store additional information in data structure

ATerm Types

- INT
- REAL
- APPL
- LIST
- PLACEHOLDER
- BLOB (Binary Large OBject)
- ANNOTATION

Examples

- 1 3.14 -0.7E34
- f(a,b) "test!"(1, 2.1, "hello")
- [] [1, 2, "abc"]
- <int> f(<int>, <real>)
- BLOBs
  - used to encode images, binary files, ...
  - have no textual representation

The ATerm Implementation

- C and Java API
- Only applicative operations
  - No destructive operations on ATerms
- Maximal subterm sharing
- Automatic garbage collection
- Binary encoding (BAF: Binary ATerm Format)

The ATerm C API

- Level 1: 41 functions
- Level 2: 80 functions (superset of Level 1)
- All function start with `AT`
- Defines types `ATerm` and `ATbool`
- Make and Match
- Read and Write
- Annotate

Intermezzo: Patterns

- A pattern is an ATerm with placeholders:
  `incr(<int>)`
- A string pattern is a pattern represented as string:
  `"incr(<int>)"`
- A string pattern resembles the format string in `printf/scanf` in C
- Placeholders correspond to typed arguments of `ATmake/ATmatch`

Make and Match

- ATerm ATmake(String p, ATerm a1, ...)
  - parse p and fill placeholders with a1, a2, ...
- ATerm ATmatch(ATerm t, String p, ATerm *a1, ...)
  - match t against p; assign subterms at placeholders to a1, a2,...
- ATbool ATisEqual(ATerm t1, ATerm t2)
- int ATgetType(ATerm t)

Read and Write

- ATerm ATreadFromString(String s)
- ATerm ATreadFromTextFile(File f)
- ATerm ATreadFromBinaryFile(File f)
- ATbool ATwriteToTextFile(ATerm t, File f)
- ATbool ATwriteToBinaryFile(ATerm t, File f)
- char *ATwriteToString(ATerm t)

Annotate

- ATerm ATsetAnnotation(ATerm t, ATerm l, ATerm a)
  - add annotation [l, a] to copy of t
- ATerm ATgetAnnotation(ATerm t, ATerm l)
- ATerm ATremoveAnnotation(ATerm t, ATerm l)

Other Functions in the Level 1 API

- Variations on the preceeding functions
- ATprintf
- handlers (warnings and errors)
- protect/unprotect

Structure of an ATerm-based Application

```
#include <stdio.h>
#include <aterm1.h>

int main(int argc, char * argv[])
{
 ATerm bottomOfStack;
 ATinit(argc,argv,&bottomOfStack);
 foo();
 return 0;
}
```

Needed for garbage collector

Initialize ATerm library

Application code goes here

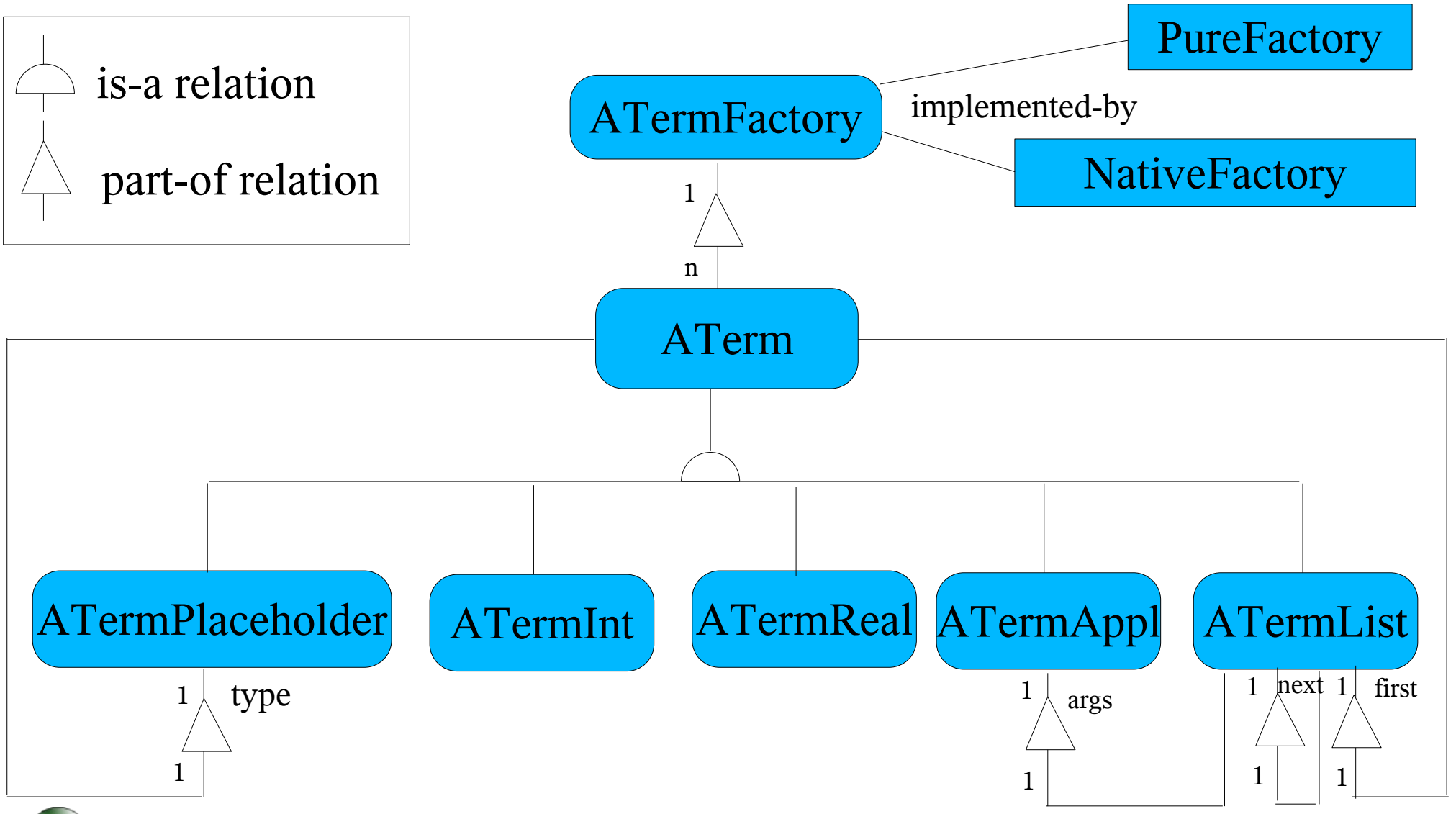
The Level 2 API

- Detailed operations for efficient ATerm manipulation
- Dictionaries
- Tables
- Indexed sets

The Java API

- Two versions:
  - Native (uses the C version via JNI, not implemented)
  - Pure (a pure Java reimplementation)
- Interface `ATermFactory` encapsulates the whole API
- Separate interfaces for each kind of ATerm (`AFun`, `ATermList`, etc.)

Class Structure



Using ATermFactory

```
import aterm.*
factory = new PureFactory();
ATerm t1 = factory.makeInt(3)
ATerm t2 = factory.readFromFile("test.trm");
ATerm t3 = factory.makeAFun("f1", 1, false);
ATerm t4 = factory.make("f(<int>)", 3);
ATerm t5 = factory.parse("f(1, [a, b])");
```

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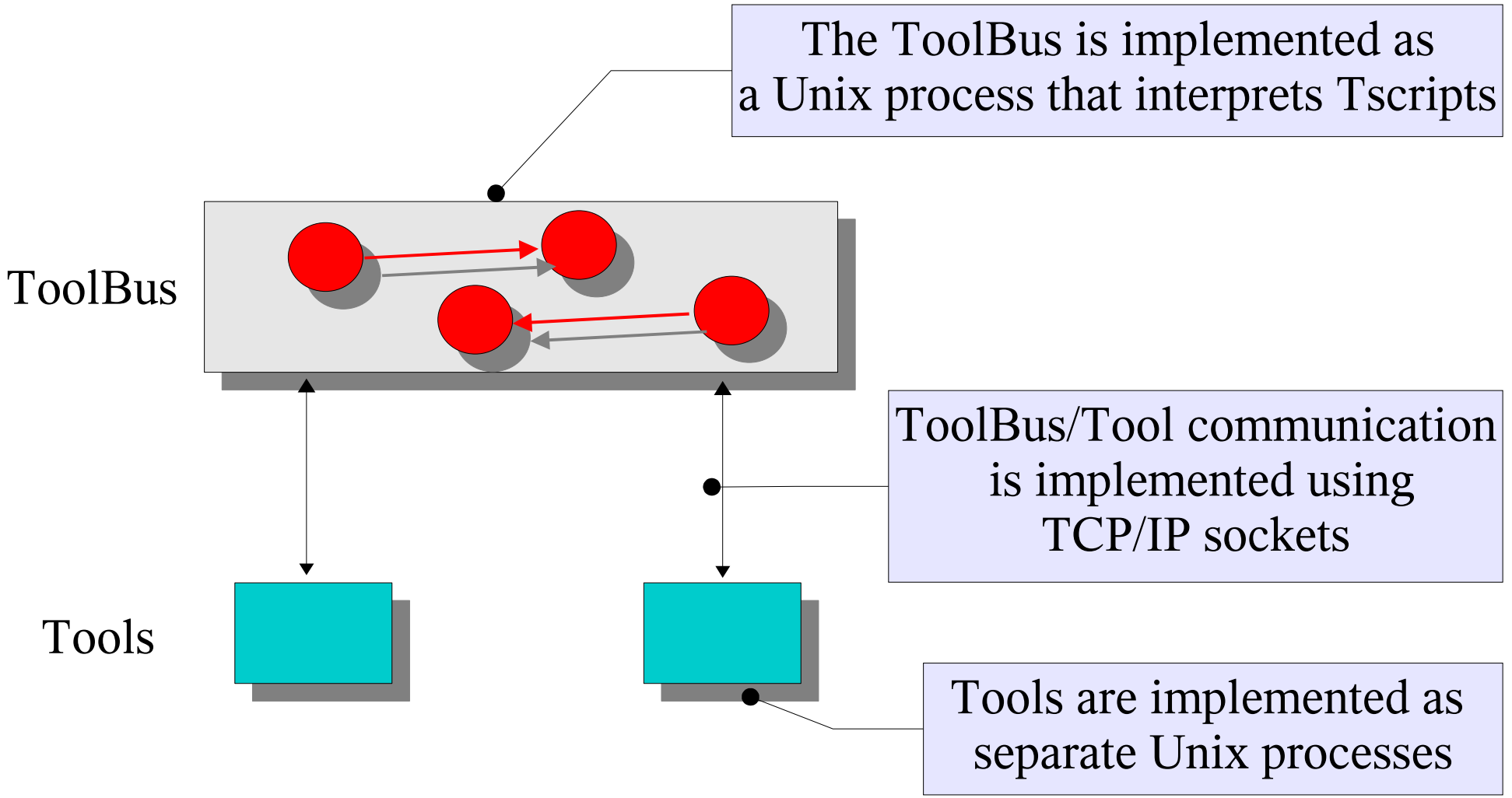
ToolBus design/implementation method

- Specification of ToolBus using ASF+SDF
- Execution of small test cases
  - Tool behaviour is defined very abstractly
- Hand translation of ASF+SDF specification to C
  - Literal translation of Tscripts
  - Implementation of tools is more concrete (see later)
- Very few bugs in ToolBus implementation
  - Some bugs turned out to be bugs in the specification!

The ToolBus implementation



The ToolBus Interpreter

- Syntax analysis of Tscript (lex/yacc)
- Typechecking of Tscript
- Create the initial ToolBus configuration
- Start execution
- Delays and timeouts
- Garbage collection of terms

The ToolBus Interpreter

- Execute tools as separate Unix process
- On creation: send expected input signature to tool
  - Permits detection of Tscript/tool mismatches
- During execution of tool: check terms received from tool against their output signature
  - Permits detection of misbehaving tools
- Enforce ToolBus protocol for each tool

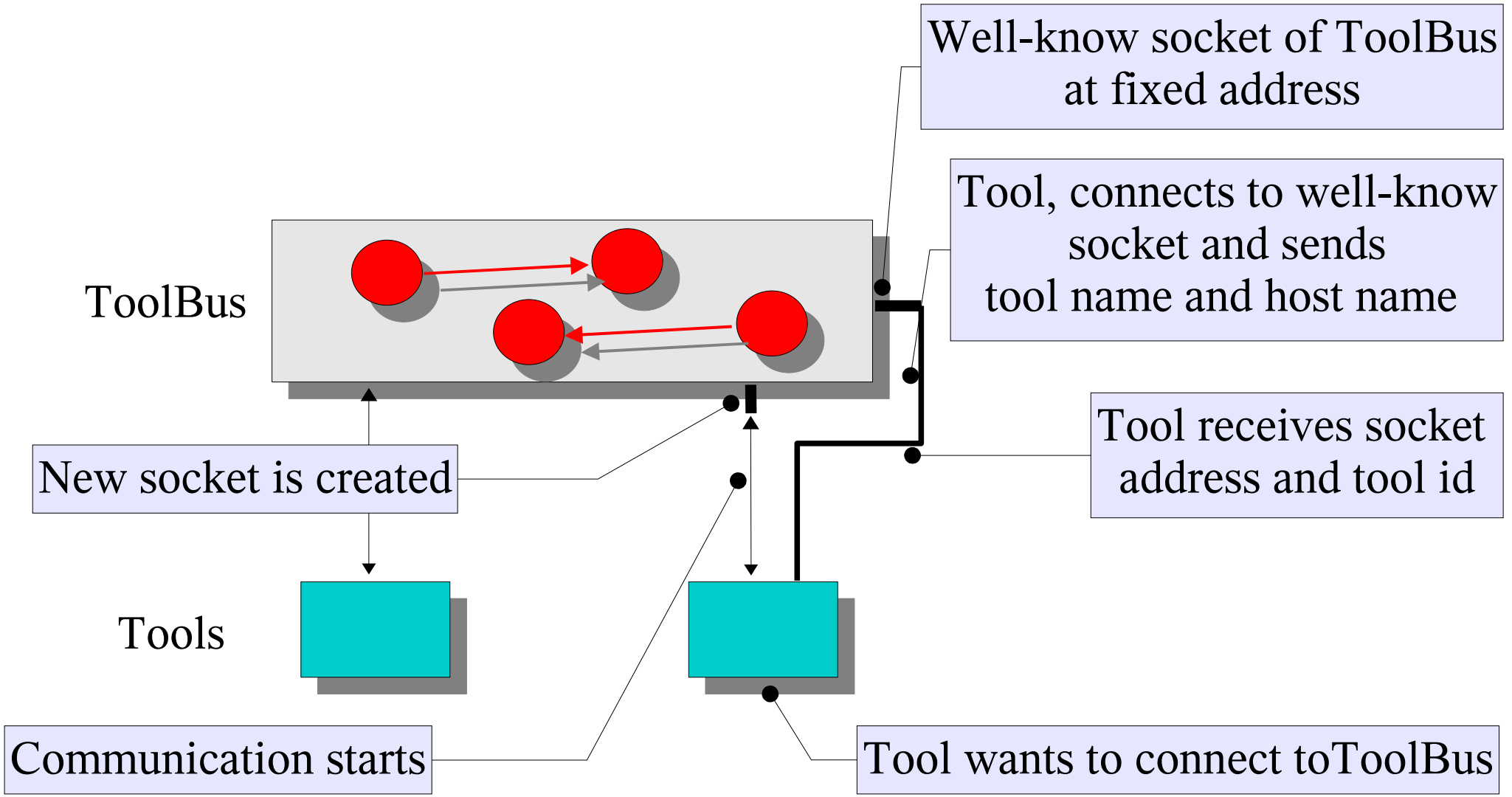
Main Interpreter Loop

- Wait for
  - an event coming from one of the tools
  - expiration of a timer
- Compute effect of event/timer on ToolBus state
- Perform any enabled atomic actions
- Repeat as long as possible
- Go back to waiting state

ToolBus Interpreter

- Interpreter maintains a lists of processes
- Each process is compiled into a finite automaton with an action associated with each transition
  - From the enabled actions one is selected randomly and executed
  - The process goes to corresponding next state
- A `select` system call waits for i/o on any socket or expiration of timer

ToolBus/tool connection



Implementation considerations

- Terms are linearized before sending and parsed when receiving them
- There is a separate transport layer that provides byte level messages of given length (to avoid system dependent segmentation of the byte stream)

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Recall the Hello World script

```
process HELLO is printf("Hello world, my first Tscript!\n")

toolbus(HELLO)
```

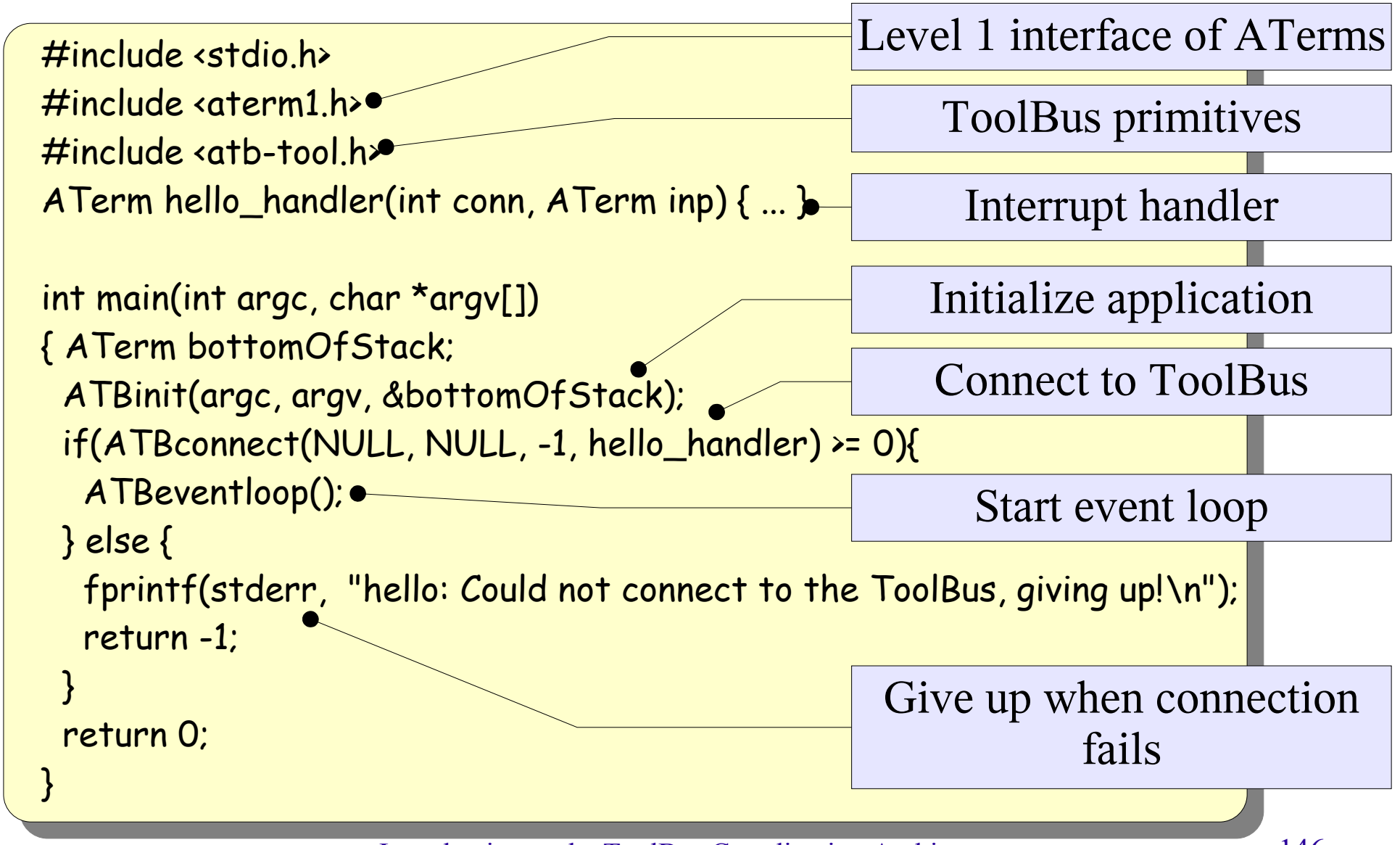
Hello World: string generated by tool

```
process HELLO is
  let H : hello,
      S : str
  in
      execute(hello, H?) .
      snd-eval(H, get-text) .
      rec-value(H, text(S?)) .
      printf(S)
  endlet

tool hello is {command = "hello" }
toolbus(HELLO)
```

How can we implement this tool?

First version of a hello tool (C)

```
#include <stdio.h>
#include <aterm1.h>
#include <atb-tool.h>
ATerm hello_handler(int conn, ATerm inp) { ... }

int main(int argc, char *argv[])
{ ATerm bottomOfStack;
  ATBinit(argc, argv, &bottomOfStack);
  if(ATBconnect(NULL, NULL, -1, hello_handler) >= 0){
    ATBeventloop();
  } else {
    fprintf(stderr,  "hello: Could not connect to the ToolBus, giving up!\n");
    return -1;
  }
  return 0;
}
```



hello_handler

```
ATerm hello_handler(int conn, ATerm inp)
{ ATerm arg, isig, osig;

  if(ATmatch(inp, "rec-eval(get-text)"))
    return ATmake("snd-value(text(\"Hello World, my first ToolBus tool in C!\n\"))");
  if(ATmatch(inp, "rec-terminate(<term>)", &arg))
    exit(0);
  if(ATmatch(inp, "rec-do(signature(<term>,<term>))", &isig, &osig)){
    return NULL;
  }
  ATerror("hello: wrong input %t received\n", inp);
  return NULL;
}
```

get-text

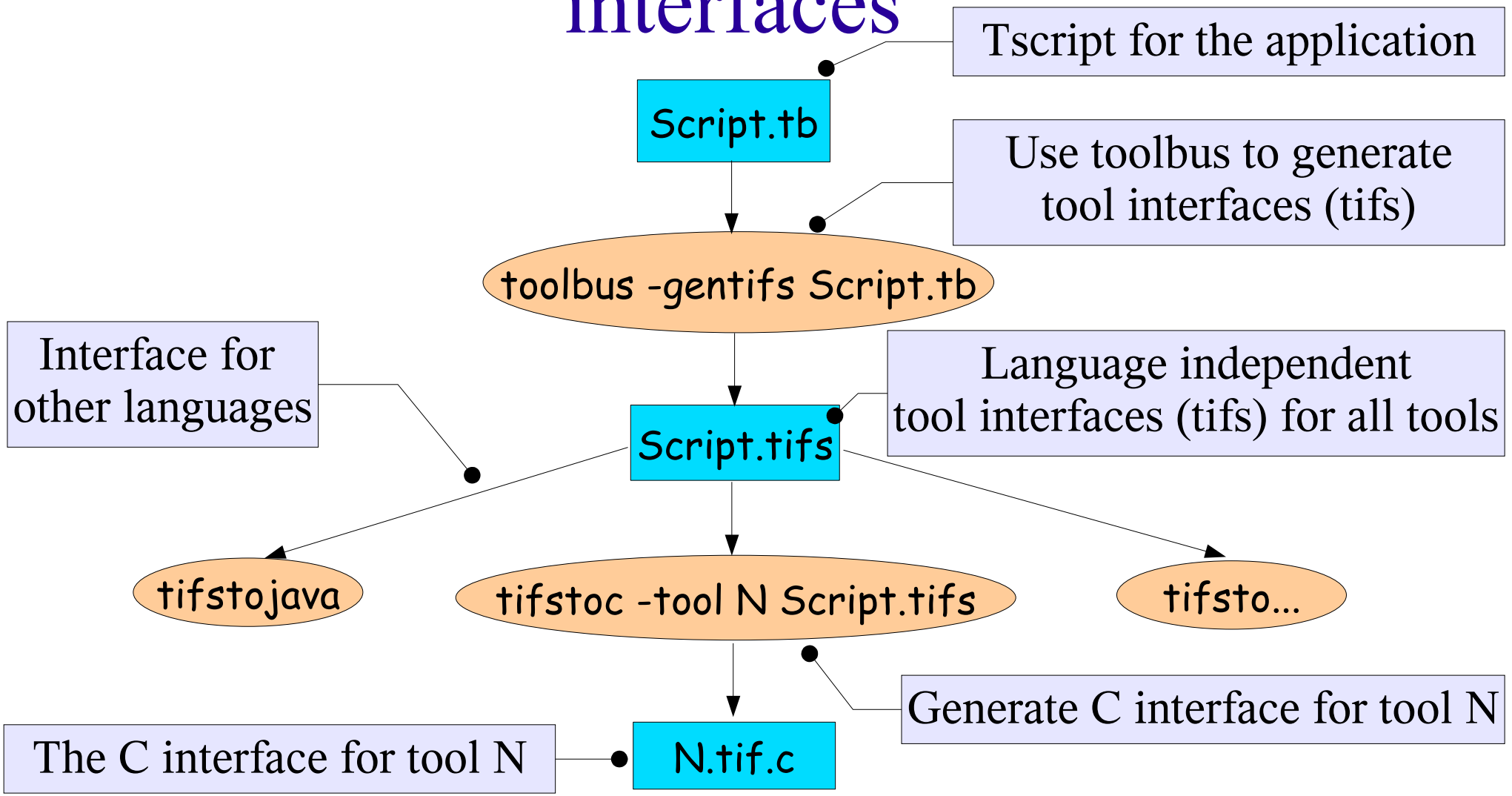
terminate

receive input signature

Observations

- Tool consists of main and an event handler
- All processing is routed via the event handler
- Event handler does repetitive (and error prone) decoding of requests using `ATmatch`
- Event handler takes care of standard messages for termination, signature handling, etc.
- Why not automate some of these tasks?

Automatic generation of tool interfaces



Second version of hello tool

```
#include "hello.tif.c"

ATerm get_text(int conn)
{
  return ATmake("snd-value(text(\"Hello World, my first ToolBus tool in C!\n\"))");
}

void rec_terminate(int conn, ATerm msg)
{
  exit(0);
}

int main(int argc, char *argv[])
{  ... as before ...
}
```

Include the generated C interface

C functions for the **get-text** and **terminate** requests

Generated file hello.tif.c

```
#include "hello.tif.h"
#define NR_SIG_ENTRIES  2

static char *signature[NR_SIG_ENTRIES] = {
  "rec-eval(<hello>,get-text)",
  "rec-terminate(<hello>,<term>)",
};

ATerm hello_checker(int conn, ATerm siglist)
{
  return ATBcheckSignature(siglist, signature,
                           NR_SIG_ENTRIES);
}
```

Prototypes of generated C functions

The signature of this tool

Checker for input signature

Generated file hello.tif.c

```
ATerm hello_handler(int conn, ATerm term)
{ ATerm in, out, t0;

  if(ATmatch(term, "rec-eval(get-text)")) {
    return get_text(conn);
  }
  if(ATmatch(term, "rec-terminate(<term>)", &t0)) {
    rec_terminate(conn, t0);
    return NULL;
  }
  ...
}
```

Call user-defined function get_text

Call user-defined function rec_terminate

Generated file hello.tif.c

```
ATerm hello_handler(int conn, ATerm term)
{ ...
  if(ATmatch(term, "rec-do(signature(<term>,<term>))", &in, &out)) {
    ATerm result = hello_checker(conn, in);
    if(!ATmatch(result, "[]"))
      ATfprintf(stderr, "warning: not in input signature:\n\t%t\n\tl\n", result);
    return NULL;
  }

  ATerror("tool hello cannot handle term %t", term);
  return NULL; /* Silence the compiler */
}
```

A larger example: the calc tool

```
process CALC is
   let Tid : calc, E : str, V : term
   in
       execute(calc, Tid?).
        (
           rec-msg(compute, E?) .
           snd-eval(Tid, expr(E)) . rec-value(Tid, val(V?)) .
            snd-msg(compute, E, V) . snd-note(compute(E, V))
         )* delta
   endlet

tool calc is { command = "calc"}
```

A larger example: the calc tool

```
#include <stdlib.h>
#include "calc.tif.c"

ATerm expr(int conn, char *s)  { ... }
void rec_terminate(int conn, ATerm t) { ... }
int calculate(ATerm t)  { ... }

int main(int argc, char *argv[])
{ ATerm bottomOfStack;
  ATBinit(argc, argv, &bottomOfStack);
  if(ATBconnect(NULL, NULL, -1, calc_handler) >= 0){
    ATBeventloop();
  } else
    fprintf(stderr, "calc: Could not connect to the ToolBus, giving up!\n");
  return 0;
}
```

Three user-defined functions

A larger example: the calc tool

```
ATerm expr(int conn, char *s)
{ ATerm trm = ATmake(s);

  if(!trm)
    return ATmake("snd-value(calc-error(<str>))", s);
  else
    return ATmake("snd-value(val(<int>))",
calculate(trm));
}

void rec_terminate(int conn, ATerm t)
{ exit(0);
}
```

Try to convert argument string to term

Calculate its value

Send that value back to the ToolBus

Handle termination

A larger example: the calc tool

Recursive evaluation of the expression

```
int calculate(ATerm t)
{ int n; char *s; ATerm t1, t2;

  if(ATmatch(t, "<int>", &n))
     return n;
  else if(ATmatch(t, "<str>", &s))
      return atoi(s);
  else if(ATmatch(t, "plus(<term>,<term>)", &t1, &t2))
      return calculate(t1) + calculate(t2);
  else if(ATmatch(t, "times(<term>,<term>)", &t1, &t2))
      return calculate(t1) * calculate(t2);
  else {
       ATerror("panic in calculate: %t\n", t);
       return 0;
      }
}
```

Road map

- The problem: component interconnection
- ...
- Implementation issues
  - Overview of the ATerm API
  - Brief overview of the ToolBus implementation
  - Writing ToolBus tools
  - Using ToolBus adapters
- Conclusions

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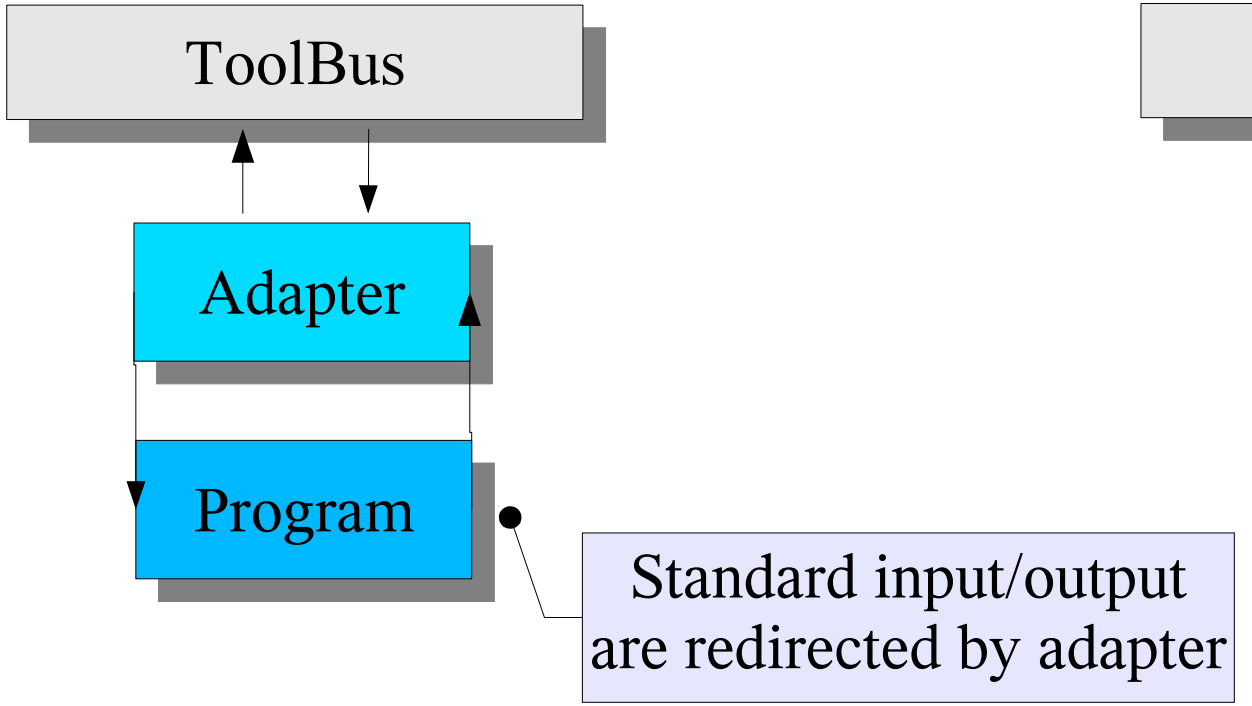
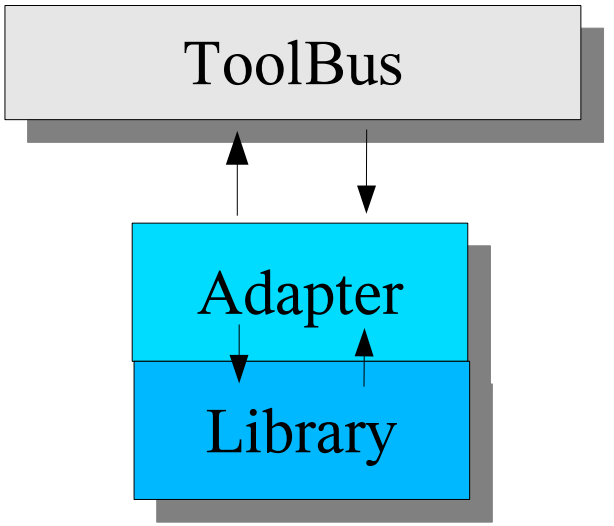
ToolBus Adapters

- Needed to adjust existing programs/libraries to the ToolBus

Separate program:



Library:



A selection of adapters

- wish-adapter: execute Tcl/Tk windowing shell
- tcltk-adapter: ditto but uses the Tcl/Tk library†
- java-adapter: java program as tool
- perl-adapter: perl program as tool†
- python-adapter: python program as tool†
- gen-adapter: arbitrary Unix command as tool†

† = not yet supported in Java-based ToolBus

The wish-adapter

- Execute Tcl/Tk's windowing shell as a tool
- Ex. `wish-adapter -script calculator.tcl`
  - `-script`: The Tcl script to be executed
  - `-script-args`: Arguments for the Tcl script
- The command wish is executed once and all further requests are directed to this instance of wish

The wish-adapter

- snd-eval(*Tid*, *Fun*(A_1,...,A_n)): perform the Tcl function call *Fun* A_1 ... A_n
- rec-value(*Tid*, *Res*?): return value for previous eval request
- rec-event(*Tid*, A_1,...,A_n): event generated by wish
- snd-ack-event(*Tid*, A_1): ack previous event
- snd-terminate(*Tid*, A_1): terminate wish-adapter

The gen-adapter

- Execute arbitrary Unix command as tool
- Example: gen-adapter -cmd ls -l
- snd-eval(*Tid*, cmd(*Cmd*, input(*Str*)): execute the Unix command *Cmd* with *Str* as standard input
- rec-value(*Tid*, output(*Res*?)): receive the standard output *Res* from a previous command
- snd-terminate(*Tid*, *Arg*): terminate execution of gen-adapter

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- ToolBus scripts (Tscripts)
- Larger examples
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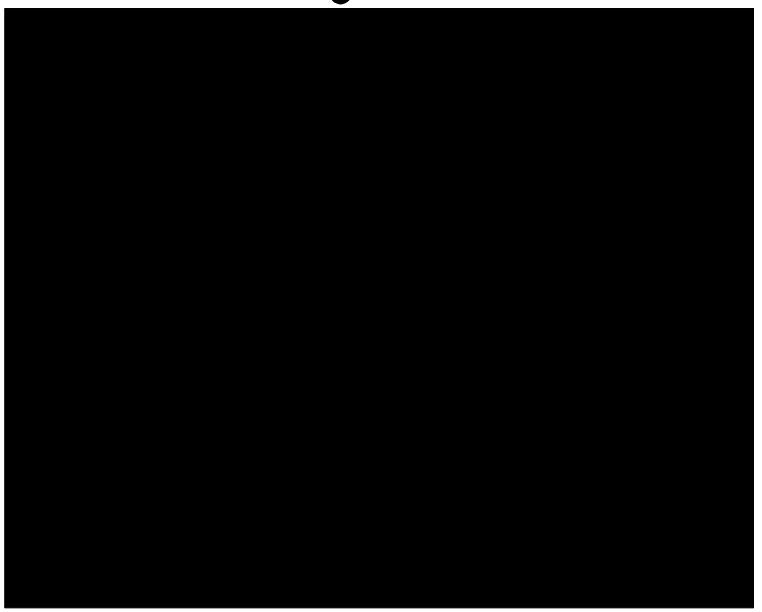
Conclusions

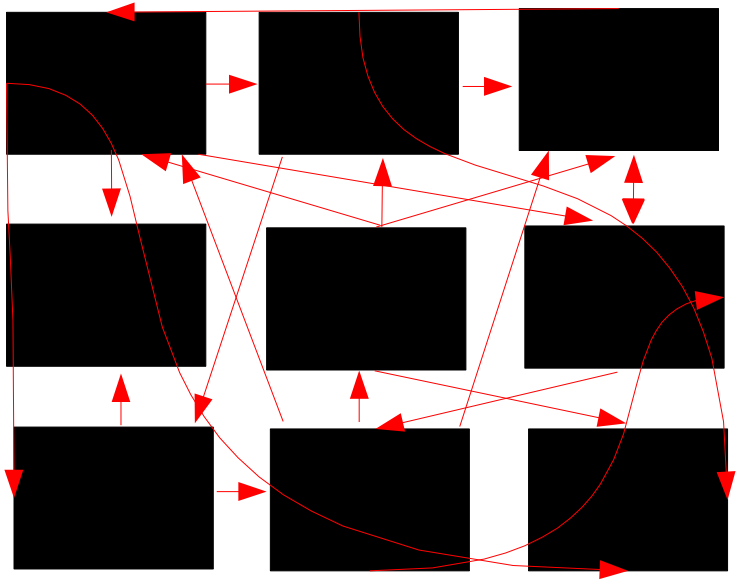
- ToolBus is an effective technology for coordination and composition of tools
- ToolBus fits in the popular model of service-oriented architectures
- ToolBus enables incremental software renovation

A Legacy System

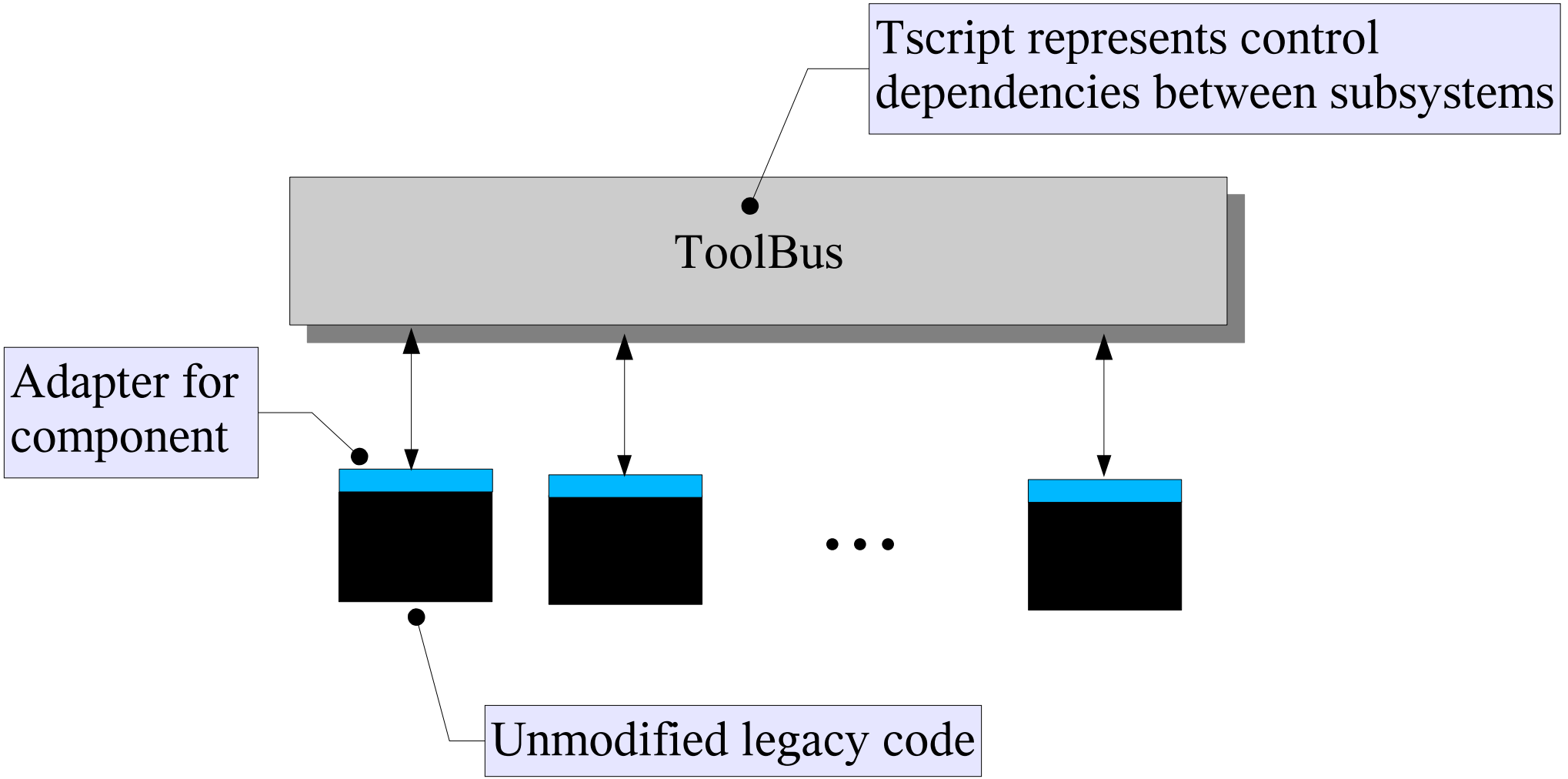
A complete blackbox:
- Subsystems unknown
- Subsystem depencies unknown



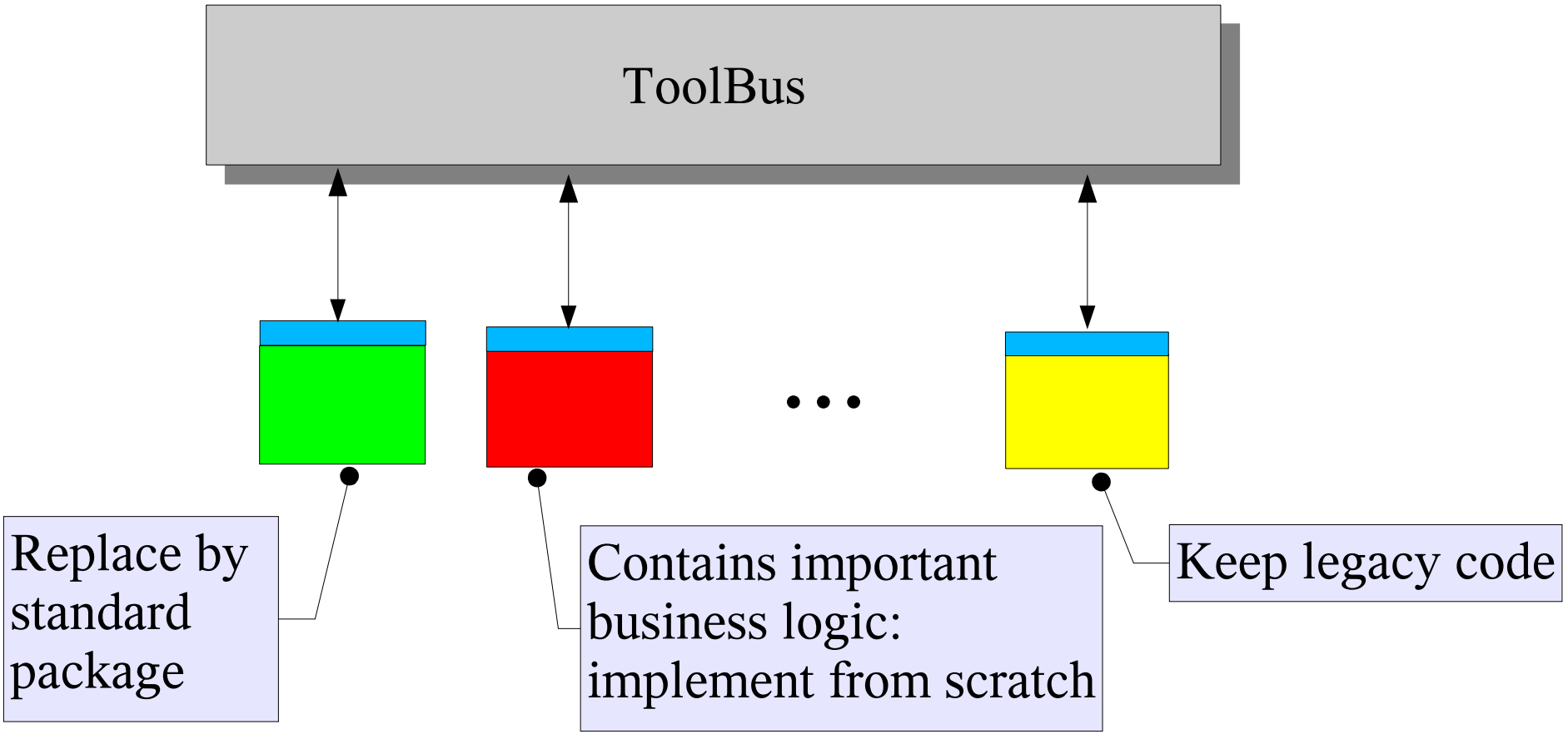
Analyze and decompose in major subsystems



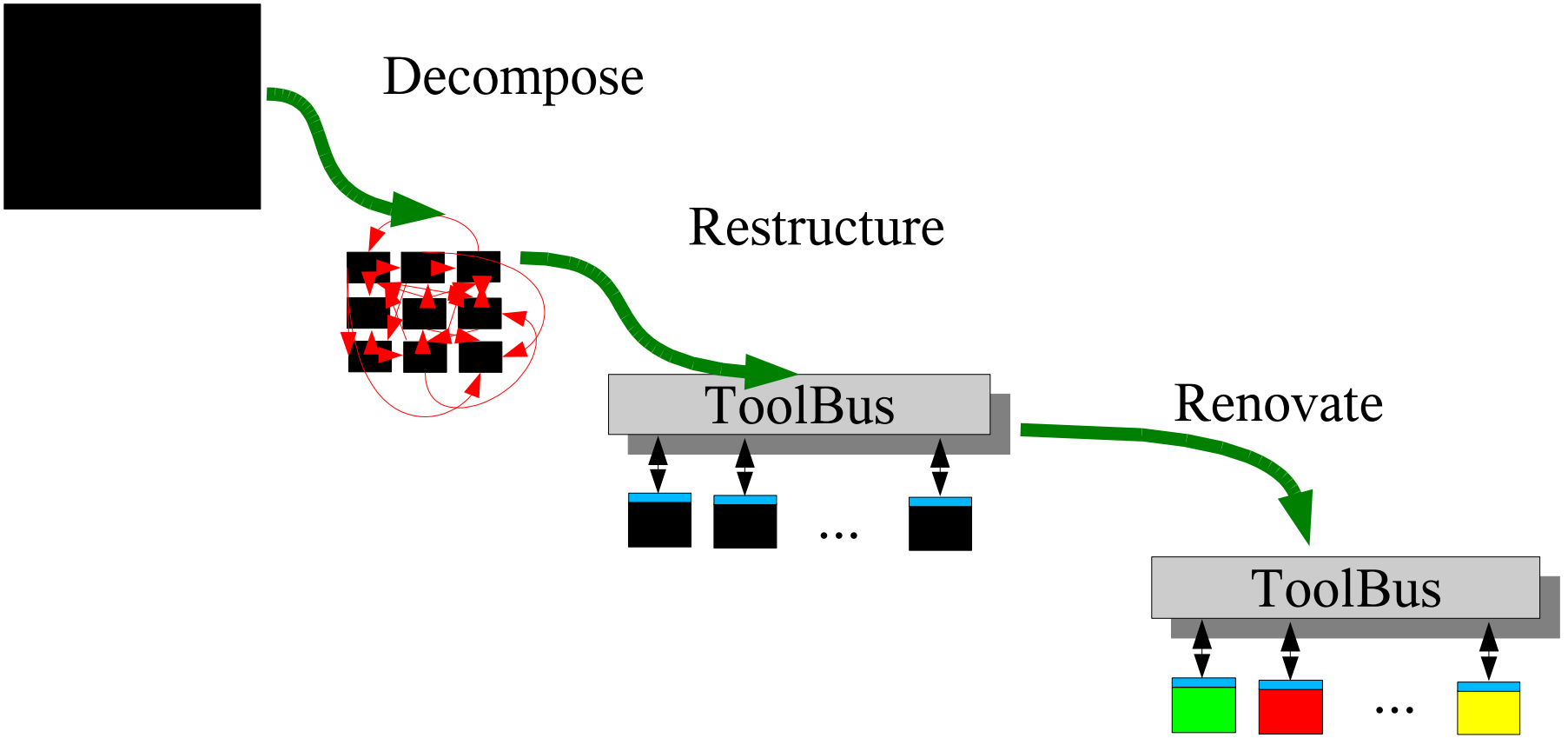
Replace dependencies by Tscript



Separate renovation strategy per subsystem



The Renovation Process



Further reading

- See at http://www.meta-environment.org (Documentation menu entry):
  - *Guide to ToolBus Programming*
  - *The ATerm Programming Guide*
  - Further references can be found in *Bibliography*