Formally Specifying and Verifying Real-Time Systems with ASTRAL

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What is a Real-Time System?

- A system whose semantics depend on the speed of execution of (some of) the activities
- A system where a failure to produce certain results within given time limits (too early ... too late) may result in an error (whose effect may be catastrophic
- A system whose performance and correctness can not be separated

Real-Time Systems

- In 1977 Wirth classified programs into three types
  - Sequential
  - Parallel
  - Processing-time dependent (i.e., real-time)

Verifying Real-Time Systems

- Sequential and real-time systems both have critical functionality requirements
- Real-time systems must also meet critical performance deadlines

ASTRAL Solution

- Develop a formal specification language
- Develop a formal proof system for proving properties about the specifications
- Build tools to support the construction and use of the specifications

Goals for ASTRAL

- Language usability was a major design factor
- Tool development proceeded in parallel with the language development
- Specifications are layered, compositional, and executable

Layered, Compositional, and Executable Specifications

- Specification modules are refined to include more detail without changing their interface
- Behavior of the whole is determined by the behavior of the parts
- Allow the developers to treat the specifications as prototypes

An Overview of ASTRAL

- In ASTRAL a real-time system is modeled by a collection of *process type specifications* and a single *global specification*
- The global specification contains declarations for types, constants, etc that are shared among process types
- A process type specification contains *types*, *state variables*, *transitions*, etc
- Every process is thought as being in various states, with one state differentiated from another by the values of *state variables*
- Only *state transitions* can change the values of state variables; Transitions are described in term of pre- and post- conditions by using an extension of first order predicate calculus

The ASTRAL Computational Model

- Maximal parallelism among processes
- Non interruptable, non overlapping transitions in a single process instance
- Transitions are executed as soon as they are enabled, that is, their pre-condition is satisfied (exception: exported transitions)
- Implicit one-to-many message passing communication
- Time can be continuous or discrete

The ASTRAL Computational Model

- Every process can export state variables and transitions
- Inter-process communication is accomplished by inquiring about the value of exported variables and the start time and end time of exported transitions.
  - i.Start(Op, t) true iff the last occurrence of transition Op of instance i started at time t.
  - i.End(Op, t) true iff the last completed occurrence of transition Op of instance i ended at time t.
  - past(expr, t) represents the value of expr at time t

The ASTRAL Computational Model

- When an exported transition fires, the start time and the values of parameters are broadcast
- When the transition ends, the end time and the values of any exported variables modified by the transition are broadcast

Environmental Assumptions

- An environment clause formalizes the assumptions that must always hold on the behavior of the external environment
- For each process there is a local environment clause which expresses the assumptions about calls to the exported transitions
- There is also a global environment clause which is a formula that may refer to all exported transitions in the system

Environmental Assumptions

- An exported transition can fire only after it has been called by the environment
- If Op is an exported transition, Call(Op,t) is true iff at time t the last occurrence of the call to Op occurred

System Assumptions

- Each process p may have an imported variable clause which formalizes assumptions that process p makes about the context provided by the other processes in the system

Critical Requirements

Critical requirements are expressed by means of:

- invariants (global and local)
- schedules (global and local)

Invariants

- Must be true regardless of the environment or the context in which the process or system is running
- State properties that must initially be true and must be guaranteed during system evolution

Schedules

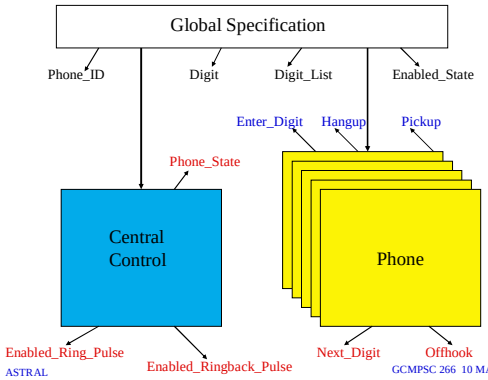
- Schedules are additional system properties that are required to hold under more restrictive hypothesis than invariants
- Assumptions expressed in the associated environment, imported variable clauses and/or system assumptions may be used to prove the validity of a schedule

Further Assumptions and Restrictions Clause

- Used to prove that schedules are feasible
- Serve only as a guidance to the implementer
- Further environment assumptions
- Further process assumptions (FPAp) section restricts the possible system implementations and reduces the level of nondeterminism of the system specification
  - transition selection part
  - constant refinement part

Telephony Example

- Two process type specifications
  - Phone
  - Central Control
- One instance of central control
- One instance of phone for each operating telephone number in the area



Keywords

Now	Represents the current value of time
Self	Is used by a process when it wants to refer to its own id

Specification Function

IDTYPE	Returns the process type when presented with a process id

Global

```
PROCESSES
   Phones: array[1 .. Num_Phone] of Phone,
   Central: Central_Control
TYPE
   Positive_Integer i: Integer (i > 0),
   Digit IS TYPEDEF d: Integer (d ≥ 0 & d ≤ 9),
   Digit_List IS LIST OF Digit,
   Phone_ID IS TYPEDEF pid: ID
            (IDTYPE(pid)=Phone)
   Enabled_State = (Idle,Ready_To_Dial,Dialing,
       Ringing,Waiting,Talk,Disconnect,Busy,Alarm)
```


Global

```
CONSTANT
   Num_Phone, Max_Cust : Positive_Integer
```

Phone

IMPORT
  Digit, Phone_ID, Enabled_State,
  Central.Phone_State,
  Central.Enabled_Ring_Pulse,
  Central.Enabled_Ringback_Pulse

EXPORT
  Offhook, Next_Digit, Pickup, Enter_Digit,
  Hangup

Phone

VARIABLE
  Offhook, Dialtone, Ring, Ringback,
    Busytone: Boolean,
  Next_Digit: Digit

Phone

TRANSITION Pickup T1
  ENTRY
    ~Offhook
  EXIT
    Offhook
    & ~Dialtone
    & ~Busytone
    & ~Ring
    & ~Ringback

Phone

TRANSITION Start_Tone T2
  ENTRY
    Offhook & ~Dialtone
    & Central.Phone_State(Self)=
      Ready_To_Dial
    & FORALL t:Time(
      Change(Dialtone,t) →
        t < Change(Offhook))
  EXIT
    Dialtone

Phone

TRANSITION Enter_Digit(D:Digit) T4
  ENTRY
    Offhook
    & (
  Central.Phone_State(Self)=Ready_To_Dial
  & Dialtone
    | Central.Phone_State(Self)=Dialing)
  EXIT
    Next_Digit=D & ~Dialtone

Other Phone Transitions

Start_Ring
Stop_Ring
Start_Ringback
Stop_Ringback
Start_Busytone
Stop_Busytone
Hangup

Phone Environment

ENVIRONMENT
FORALL t: Time (Call(Pickup, t) →
~past(Offhook, t))
& FORALL t: Time (Call(Hangup, t) →
past(Offhook, t))
& FORALL t: Time ($Call_2$(Pickup, t) →
Call(Pickup) - $Call_2$(Pickup) ≥ 1)

Phone Environment

FORALL t: Time
(Call(Enter_Digit, t)
→ (past(Dialtone, t)
| EXISTS t1: Time, n: Integer, D: Digit
(2 <= n & Calln(Enter_Digit(D), t1)
& past(Dialtone, t1) & n <= 7
& FORALL t2: Time (t1 <= t2 <= t
→ past(Offhook, t2))))

Phone Invariant

INVARIANT
(Dialtone → ~Ring & ~Ringback & ~Busytone)
& (Ring → ~Dialtone & ~Ringback & ~Busytone)
& (Ringback → ~Dialtone & ~Ring & ~Busytone)
& (Busytone → ~Dialtone & ~Ring & ~Ringback)

Phone Schedule

SCHEDULE
FORALL t: Time (
Call(Pickup, t) <–>Start(Pickup, t))

Phone Further Assumption

FURTHER ASSUMPTION #1
FURTHER PROCESS ASSUMPTION
TRANSITION SELECTION
enabled_transitions CONTAINS
any_subset({Stop_Ringback, Stop_Busytone})
& TRUE
→ eligible_transitions =
{Stop_Ringback, Stop_Busytone}
INTERSECT enabled_transitions

Central Control

IMPORT
Digit, Digit_List, Phone_ID, Enabled_State,
Phones.Offhook, Phones.Next_Digit,
Phones.Pickup, Phones.Enter_Digit

EXPORT
Phone_State, Enabled_Ring_Pulse,
Enabled_Ringback_Pulse

Central Control

```
VARIABLE
   Phone_State(Phone_ID): Enabled_State,
   Enabled_Ring_Pulse(Phone_ID):Boolean,
   Enabled_Ringback_Pulse(Phone_ID): Boolean,
   Connected_To(Phone_ID): Phone_ID,
   Number(Phone_ID): Digit_List
```


Central Control

```
IMPORTED VARIABLE CLAUSE
  SETSIZE( { SETDEF P: Phone_ID (
      Now - 2 <= P.Start(Pickup) <= Now)} )
            <= Max_Cust
```


Central Control

```
TRANSITION
      Give_Dial_Tone(P:Phone_ID)    Tim1
  ENTRY
          P.Offhook
        & Phone_State(P)=Idle
  EXIT
          Phone_State(P) BECOMES
                        Ready_To_Dial
        & Number(P) BECOMES NIL
```


Central Control

```
TRANSITION
      Process_Digit(P:Phone_ID)   Tim2
 ENTRY
        P.Offhook
      & Count(P) < 7
      & ( (   Phone_State(P)=Ready_To_Dial
          & P.End(Enter_Digit) > End(Give_Dial_Tone(P)))
        | (   Phone_State(P)=Dialing)
          & P.End(Enter_Digit) > End(Process_Digit(P))))
  EXIT
      Number(P) BECOMES Number'(P) CONCAT LISTDEF(P.Next_Digit)
      & Phone_State(P) BECOMES Dialing
```


Other Central Control Transitions

Process_Call
Enable_Ring_Pulse
Disable_Ring_Pulse
Enable_Ringback_Pulse
Disable_Ringback_Pulse
Start_Talk
Terminate_Call
Generate_Alarm

Central Control Invariant

```
INVARIANT
   FORALL P:Phone_ID (
      Count(P) >= 0  &  Count(P) <= 7
    & Phone_State(P)=Waiting →
            Phone_State(Connected(P))=Ringing
    & Phone_State(P)=Ringing →
      Phone_State(Connected(P))=Waiting
    & Phone_State(P)=Talk →
```

Central Control Constraint

```
CONSTRAINT
    FORALL P:Phone_ID (
          (  Phone_State'(P)=Busy
           | Phone_State'(P)=Alarm
           | Phone_State'(P)=Disconnect)
         & Phone_State(P) ~= Phone_State'(P)
        →
         Phone_State(P)=Idle )
```


Central Control Schedule

```
SCHEDULE
  FORALL P:Phone_ID (
       Phone_State(P)=Ringing
    & Now - End(Process_Call(Connected(P))) >= Downtime_Ring
  →
    EXISTS n:Integer (
        Endn(Enable_Ring_Pulse(P)) >
              End(Process_Call(Connected(P)))
     & Endn(Enable_Ring_Pulse(P)) <=
              End(Process_Call(Connected(P))) + Downtime_Ring )
                        )
```


Global Environment

```
ENVIRONMENT
  SETSIZE({ SETDEF P: Phone_ID (
      Now - 2 <= P.Call(Pickup) <= Now)} )
           <= Max_Cust
```


Global Schedule

```
SCHEDULE
  FORALL P:Phone_ID, t: Time
        (     P.Offhook
          &  P.Call(Pickup, t)
          &  Now - t >= 2
          &  past(Central.Phone_State(P), t) = Idle
        → EXISTS t1:Time (t < t1 <= t + 2
                    & past(Central.Phone_State(P), t1)
                              = Ready_To_Dial))
```


Formal Proofs

Formal proofs in ASTRAL can be divided into two categories:

- Intra-level proofs
- Inter-level proofs

Formal Proofs

- Intra-level proofs deal with proving that the specification of level i is consistent and satisfies the stated critical requirements
- Inter-level proofs deal with proving that the specification of level i+1 is consistent with the specification of level i

ASTRAL Intra-level Proofs

- Every process specification guarantees its local invariant
- Every process specification guarantees its local schedule
- The specification guarantees the global invariant
- The specification guarantees the global schedule
- The imported variable assumptions are guaranteed by the specification
- All the assumptions about the environment are compatible

Building an ASTRAL intra-level proof

- The local invariant Ip describes properties which are independent from the environment, i.e., it must hold in every possible environment
- To prove that the process Pp guarantees Ip we have to show that:
  1) Ip holds in the initial state of process p, and
  2) If Pp is in a state in which Ip holds, then for every possible evolution of Pp, Ip will hold.

Building an ASTRAL invariant proof

1) Init_Statep & Now = 0 → Ip

2) We assume that Ip holds until a given time t0 and prove that Ip will hold for every time t > t0. Without loss of generality we assume that t = t0 + Δ, for some fixed Δ > 0 and we will show that Ip holds until t0 + Δ

   We may need to make assumptions on the possible sequences of events that occurred within the interval [t0 - H, t0 + Δ], where H is a constant *a priori* unbounded. By event we mean the starting (ending) of some transition of Pp

ASTRAL Abstract Machine Semantics

Captured in three axioms

A1 start to end of transition is equal to the transition duration

A2 if processor is idle and some transitions are enabled, then one will fire

A3 for each processor the transitions are nonoverlapping

Axiom A1

FORALL t:Time, Op: Trans_of_p
(Now - t ≥ TOp
→ (past(Start(Op),t) = t
↔ past(End(Op),t+TOp) = t +TOp))

where TOp represents the duration of Op

Axiom A2

FORALL t:Time (
EXISTS d:Time, S'T: SET OF Trans_of_p(
FORALL t1:Time, Op: Trans_of_p(
t1 ≥ t - d & t1 < t & Op ISIN ST
& past(Start(Op),t1) < past(End(Op),t)
& S'T ⊆ ST & S'T ~= EMPTY
& FORALL Op':Trans_of_p (
Op' ISIN S'T → Eval_Entry(Op',t))
& FORALL Op':Trans_of_p (
Op' ~ISIN S'T → ~Eval_Entry(Op',t))
→ UNIQUE Op':Trans_of_p (
Op' ISIN S'T & past(Start(Op'),t)=t))))

Axiom A3

FORALL t1, t2:Time, Op: Trans_of_p(
Start(Op)=t1 & End(Op)=t2 & t1 < t2
→ FORALL t3: Time, Op': Trans_of_p(
t3 ≥ t1 & t3 < t2 & Start(Op')= t3
→ Op = Op' & t3 = t1)
& FORALL t3: Time,Op': Trans_of_p(
t3 > t1 & t3 ≤ t2 & End(Op')= t3
→ Op = Op' & t3 = t2))

Building an ASTRAL invariant proof

- For each sequence of events σ a formula Fσ can be algorithmically associated with σ
- For each event occurring at time t we have:

  - past(ENpj, t) & past(Start(Oppj, t), t) if the event is the start of Oppj

  - past(EXpj, t) & past(End(Oppj, t), t) if the event is the end of Oppj

A1 & A2 & A3 ⊢Fσ & FORALL t:Time (t <= t0 → past(I_p,t))
→ FORALL t_1 :Time (t_1 > t_0 & t_1<= t_0+Δ → past(I_p, t_1))

To Prove the Schedule

Need to modify axiom A2 to deal with the transition selection clause and to require calls for external transitions

Also need an axiom to state that a call is issued only if a call was made from the environment and not yet serviced

Axiom A2'

FORALL t:Time (
EXISTS d: Time, S'T: SET OF Trans_of_p(
FORALL t1:Time, Op: Trans_of_p(
t1 ≥ t - d & t1 < t & Op ISIN ST
& past(Start(Op),t1) < past(End(Op),t)
& S'T ⊆ ST & S'T ~= EMPTY
& FORALL Op':Trans_of_p (
Op' ISIN S'T → Eval_Entry'(Op',t))
& FORALL Op':Trans_of_p (
Op' ~ISIN S'T → ~Eval_Entry'(Op',t))
→ UNIQUE Op':Trans_of_p (
Op' ISIN TS(S'T) & past(Start(Op'),t)=t))))

Axiom A4

FORALL Op: Trans_of_p(
EXISTS t1: Time(
t1 ≤ Now & Call(Op, t1)
& FORALL t: Time (
t ≥ t1 & t ≤ Now & ~Start(Op,t)
→ past(Issued_call(Op),t)))
& EXISTS t1: Time(
t1 ≤ Now & Start(Op, t1)
& FORALL t: Time(
t > t1 & t ≤ Now & ~Call(Op,t)
→ ~past(Issued_call(Op),t))))

Building an ASTRAL schedule proof

- To prove that Pp guarantees the local schedule Scp:

  1) Scp holds in the initial state of process p, and
  2) If Pp is in a state in which Scp holds, then for every possible evolution of Pp compatible with the system assumptions, when the environment behaves as described in Pp, Scp will hold.

- We can assume that the local invariant Ip holds

Building an ASTRAL Global proof

- Proving that S guarantees the global invariant IG is done as for the local invariant case:

1) IG holds in the initial state of S, and
2) If S is in a state in which IG holds, then for every possible evolution of S, IG will hold.

- We can assume that the local invariants Ip hold

Building an ASTRAL global proof

- To prove that S guarantees the global schedule ScG:

1) ScG holds in the initial state of S, and
2) If S is in a state in which ScG holds, then for every possible evolution of S, ScG will hold

- We can assume that the global invariant, every local invariant and schedules, and the global environment assumptions hold
- We cannot use any of the local environment assumption or system assumptions to prove the validity of the global schedule

Building an ASTRAL consistency Proof

- When proving a local schedule we rely on the assumptions on the imported variables. Such assumptions must be checked against the behavior of the processes they are imported from.
- Every process contains two clauses describing assumptions on the behavior of the environment. The global specification contains another clause describing assumptions on the environment. We must verify that all the assumptions do not contradict each other

ASTRAL Inter-level Proofs

- Every transition at level n is correctly implemented at level n+1

Composing ASTRAL Specifications

Composing two top level specifications S' and S" means to build a new top level specification C, that is the specification of a system obtained by making one or more instances of S' and S" interact

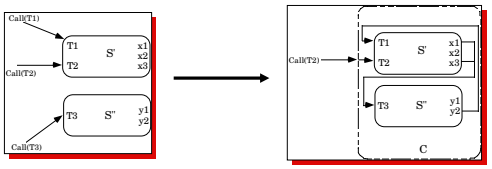
In order to compose S' and S" one has to define:
- how the interaction between S' and S" can be formally defined
- how the specification C can be built starting from S', S" and the description of their interaction
- under which conditions the critical requirements of S' and S" will still be valid in C.

The Compose Section

- The COMPOSE section allows ASTRAL specifications to be composed into a new specification of a more complex system
- By adding the COMPOSE section and introducing a compositional specification method a system designer can now reason about the behavior of a composite system in terms of its components
- The size of the composite specification grows linearly with the size of the component specifications

The Compose Section

- The COMPOSE Section describes the interaction between S' and S"
- Some exported transitions of S' (S") are no longer exported, i.e., the stimuli needed to fire such transitions are produced by S" (S') rather than the external environment



The COMPOSE Section

- The COMPOSE Section contains the following parts

- A set of clauses defining types constants and definitions
- A name clash resolution clause
- A call generation clause describing how exported transitions of S' (S") are triggered by events occuring in S" (S')

FORALL t: Time, … (P(S') ↔ Call(T, t))

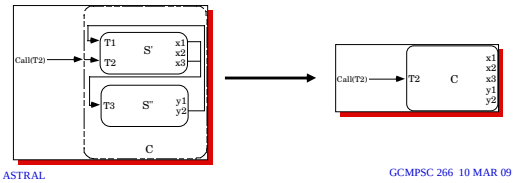
where P(S') is an ASTRAL well-formed formula describing the occurrence of events in S' equivalent to calling transition T of S"

Building the New Specification

- When composing two specifications by means of a COMPOSE section it is desirable to automaticaly produce the specification of the composed system. Therefore it is necessary to:

  - Build the global specification

  - Modify the process specifications



The Global Specification

- The clauses defining type, constants, and definitions are taken from the COMPOSE section and the global specification of S' and S" (using the name clash clause)
- The global invariant (schedule) is built from the invariants (schedules) of S' and S", by substituting any occurrences of the operators Start, End and Call referring to a no longer exported transition with an equivalent predicate referring to exported variables
- The global environment clause is similarly built by modifying those parts that refer to no longer exported transitions.

The Process Specifications

- All process specifications belonging to either S' or S" belong to C
- For each process specification the following modifications are required:

Local environment clause transitions	Remove references to no longer exported
Export/Import clause	Unexport transitions referred to in the Call Generation Clause of the COMPOSE section
	Import variables referred to in the CGC
Transitions in the CGC	Modify the Entry condition: EXISTS t: Time … (P(S') & Start(T) < t) & Old_Entry,
	P(S') is the predicate used in the CGC

The Process Specifications

Imported variables clause	Add assumptions about new imported variables They are generated from the CGC and the old environment clauses
Local Schedule	Modify as for Global Schedule
Local Invariant	No modification is required
Process assumptions	No modification is required

Proof Obligations

- Under what conditions are the invariants and schedules of S' and S" still valid in C ?

- Invariants do not depend on the environment

  Therefore, they are still valid

- Schedules do depend on the environment

  Therefore, one has to prove that the behavior of S' (S") implies what is stated in the environment clauses of S" (S'):

$$A1 \,\&\, A2'' \,\&\, A3 \,\&\, A4 \,\&\, Env_{G'} \,\&\, CG' \vdash F_{\sigma'} \rightarrow Env_{G''}, \text{ for } S''$$

$$A1 \,\&\, A2'' \,\&\, A3 \,\&\, A4 \,\&\, Env_{G''} \,\&\, CG'' \vdash F_{\sigma''} \rightarrow Env_{G'}, \text{ for } S'$$

Modularized Specifications

- The composite specification approach coupled with the top-down refinement specification approach allows a system designer to specify his/her system using either a bottom-up approach or a top-down approach or a combination of the two
- The composability of specifications also promotes the reuse of existing specifications

ASTRAL Tool Suite

In order to get designers to use formal methods to develop real-time systems it is necessary to provide them with an integrated set of tools for writing and analyzing their specifications

ASTRAL Software Development Environment (SDE)

- Syntax directed editor
- Specification processor
- Reasoning system
- Specification testing component
- Browser kit

SDE

- A key design criteria for the SDE was that a user should never need to switch between tools nor should there be any need for data exchange via temporary files
- The user should be able to change from specification writing to type checking to generating proof obligations with a mere button push

Syntax-Directed Editor

- Only basic editing functions
- Syntax is automatically checked when input
  - errors are indicated when entered
  - help facility displays corresponding part of the grammar
- When editing of a section is completed the section of text is formatted into a fixed format

Specification Processor

- Validation component checks the entire specification for:
  - type errors
  - scoping errors
  - missing parameters
- Proof obligation component generates
  - Intra-level proof obligations
  - Inter-level proof obligations
  - Composition proof obligations

Reasoning System

- Uses PVS theorem prover
  - ASTRAL semantics have been written in the PVS specification language
  - ASTRAL to PVS translator
- ASTRAL model checker

Specification Testing Tool

- Symbolically executes an ASTRAL specification under user direction
- Modification of the ASTRAL model checker

Browser Kit

- Uses three inter-related databases
  - Variables database
  - Transitions database
  - Processes database
- Automatically updated whenever the specification is edited
- Browser for each database
- Particularly useful during the maintenance phase

ASTRAL Case Studies

Standard Benchmarks
- railroad crossing
- elevator

Phone System (POTS)

Wide-area Phone System

Hardware
- checksum generator
- UART

Robot Control System

For More Information

Introduction to Language and Composition
- TSE September 1997

Intra-level Proof Obligations
- TSE August 1994

Inter-level Proof Obligations
- ESEC 95

Composability Proof Obligations
- ISSTA 93

Software Development Environment (SDE)

ftp from ftp.cs.ucsb.edu in directory seclab-distrib

Using the ASTRAL Model Checker Tool for Encryption Protocol Analysis

- DIMACS 97
- FM&SP 98

Online ASTRAL Info

www.cs.ucsb.edu/~seclab/projects/ASTRAL