Precise Specification Methods

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Starting point

- Software-based systems
  - Embedded in multiple fields
    - Financial, commercial, medical, nuclear, etc
  - More and more complex
- We are software dependent
  - We need systematic methods of construction
  - We need dedicated verification methods

What are precise specification methods?

- Usually called FORMAL METHODS
  - Fault-avoidance techniques for constructing trustworthy systems
  - Consist of a specification language and a construction and/or verification method
  - Mathematical basis
- Specification language
  - Based on logics and mathematics (has SEMANTICS!!)
  - Allows the devising of models for the system to be built by using a specific syntax
- Construction/verification method can allow
  - The specification of the required properties for verifying that
    - A model correctly captures a set of requirements
    - A more detailed model correctly develops a less detailed model of the same system
  - Various analysis types based on the devised models

Some formal methods

- CSP (Communicating Sequential Processes)
- CCS (Calculus of Communicating Systems)
  - π-calculus
- Ambient calculus
- Action systems
- UNITY
- Z
- B

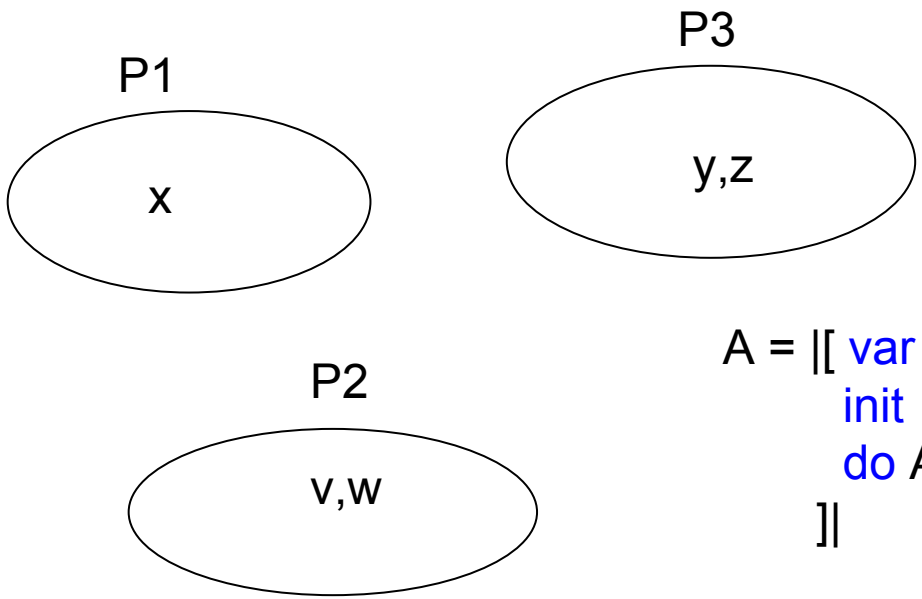
Action systems

- For modeling distributed systems
- Imperative specification language
  - State-based formalism
  - Extension of the “guarded commands” language of Dijkstra
  - Can model parallel computing
  - Based on the refinement calculus of Back
  - Semantics: wp-calculus (“weakest preconditions”)

Why action systems?

- Introduced in 1983, by Back and Kurki-Suonio
- Brings a new perspective for the modeling of distributed systems
  - Until then it was CSP and CCS – process algebras
- Extended in very many directions
  - Hardware modeling → BlueSpec, MIT
  - Hybrid systems
  - Critical systems

Action system appearance




```
A = |[ var x,y,z,v,w
       init
       do Ai od
     ]|
```

$A_i = g_i \rightarrow S_i$
A_i can be chosen for execution when g_i holds; then A_i is called *enabled*

The fundamental feature

- Refinement quality: $\mathcal{A}$, $\mathcal{B}$
  - A high level specification $\mathcal{A}$ of a program is transformed by a sequence of correctness-preserving steps into **an executable and efficient** program $\mathcal{B}$ that satisfies the original specification
  - $\mathcal{A}$ – action system; beh ($\mathcal{A}$) (*behavior of* $\mathcal{A}$): the set of state sequences that correspond to all the possible executions of $\mathcal{A}$
  - Algorithmic, data, superposition
  - <u>Algorithmic</u>: just input-output behavior kept
  - <u>Data</u>: also the reactive behavior (internal)
    - Abstraction relation R between the new and the old data
    - R models what needs to be respected by the refined version
  - <u>Superposition</u>: adding things

Algorithmic refinement

- Degree of parallelism can be increased, while correctness is kept
- *Total correctness* preserved
  - Appropriate correctness notion for parallel algorithms
  - Parallel programs differ from the sequential ones in that
    - They are executed by cooperation of processes (in parallel)
    - They are intended to terminate
    - Only their final results are of interest

Stepwise refinement of action systems

- Special rules for introducing parallelism
  - Transform sequential statements directly into iterative constructs
  - Combine iterative sub-statements into a single iterative construct
  - Change variables in sub-statements
    - Change the program state representation from centralized to distributed

Refining atomicity

- Starting point
  - Large action, possibly needing synchronization and participation of many processes over an extended time
- Replaced by
  - A number of smaller actions achieving the same effect as the larger action but exhibiting more parallelism among themselves
    - Less synchronization of processes, more overlapping of (parallel) execution
    - Less time
- Boils down to
  - Transforming the control structure: moving actions of an inner loop to the level of the outer loop

Data refinement

- Algorithmic refinement
  - does not guarantee that the behavior of $\mathcal{B}$ is the same as the behavior of A in every step of the execution
- Data refinement also preserves the reactive (internal) behavior
  - Abstraction relation **R** between data in $\mathcal{A}$ and data in $\mathcal{B}$
  - **R** acts as an invariant capturing the reactive behavior to be kept
  - Besides preserving the correctness, all changes have to also ensure **R**
- Specific rules
  - R is established by the initializations in $\mathcal{A}$ and $\mathcal{B}$
  - Each action A in $\mathcal{A}$ is data refined by its corresponding action B in $\mathcal{B}$ using R
  - For each action A, when A is enabled, then either B or an extra action H in $\mathcal{B}$ is enabled whenever R holds
  - Every extra action H in $\mathcal{B}$ is a stuttering action (acts as skip for the global variables)
  - Every extra action H in $\mathcal{B}$ terminates when executed in isolation
  - The environment preserves R

Trace refinement

- Theoretical expression of data refinement for reactive systems that
  - May / may not terminate
  - Atomic actions of the reactive systems need not terminate themselves
- Trace
  - s – behavior; $s = <(a_0, u_0), (a_1, u_1),\ldots>$
  - *Stuttering step*: an occurrence of 2 consecutive steps in s with the same global component
  - Tr(s) is the behavior s, removing all finite stuttering and keeping only the global component in each state
- Trace refinement
  - $\mathcal{A} \subseteq \mathcal{C} \Leftrightarrow \forall t \in beh(\mathcal{C}).\ \exists s \in beh(\mathcal{A}).\ s \leq t$, where $s \leq t$ (*s approximates t*) if
    - Either s is aborting and tr(s) is a prefix of tr(t)
    - Or tr(s) = tr(t) and neither s nor t are aborting
  - Difficult to use; instead simulation methods are used
  - Simulation method: constructs an abstract behavior which approximates a given concrete behavior

Superposition refinement

- $\mathfrak{S}, \mathfrak{S}' : \mathfrak{S} \subseteq \mathfrak{S}'$ if
  - Whenever $\mathfrak{S}$ is guaranteed to terminate, $\mathfrak{S}'$ is also guaranteed to terminate
  - Any possible outcome of $\mathfrak{S}'$ for some initial state is also a possible outcome of $\mathfrak{S}$ for the same initial state
- $\mathfrak{S}'$ can add data and behavior to $\mathfrak{S}$, without interfering with the behavior of $\mathfrak{S}$
  - Keep behavior of $\mathfrak{S}$
  - No influence on the behavior of $\mathfrak{S}$
  - No taking over the behavior of $\mathfrak{S}$
- In practice
  - Strengthening guards
  - Adding non-influencing and non-taking over actions

Action systems in use

- Middleware supporting the functioning of a network
  - MIDAS
- Energy-aware computing

Specification levels

Role	Specification	Represents
User	Requirements	
Application developer	Level 1 Spec	Application
Network manager	Level 2 Spec	Middleware
Programmer	Implementation	Code

MIDAS

- a middleware language
- resource-centric
- assists the network manager to treat
  - resource accessibility
  - replicated and homonym resources
  - mobility of resources
  - node failure and recovery
- based on action systems

Resources in MIDAS

- data, code, or computation units
- locations of resources
  - network: (V, Edges)
  - nodes α in the network where data can reside or where computation can take place
  - implicitly: **stationary devices**
  - Is it necessary?

MIDAS resources

- Data: (v, loc, VAL, val)
  - Data unit: variable
  - v.loc, v.val, α.var
- Code: (a, loc, A)
  - Code unit: action
  - A = g -->A.body; a.loc, A.loc, α.action
- Computation unit:

  CU = |[exp y; var x; imp z;

  do $[]_{i \in I}$ A_i od

  ]|
  - non-deterministic execution
  - atomic actions

Modularity

$$CU_1 = |[\ \text{exp}\ y_1;\ \text{var}\ x_1;\ \text{imp}\ z_1;\ \text{do}\ []_{i \in I}\ A_i\ \text{od}\ ]|$$

$$CU_2 = |[\ \text{exp}\ y_2;\ \text{var}\ x_2;\ \text{imp}\ z_2;\ \text{do}\ []_{j \in J}\ A_j\ \text{od}\ ]|$$

$$CU_1 \parallel CU_2 = |[\ \text{exp}\ y_1 \cup y_2;\ \text{var}\ x_1 \cup x_2;\ \text{imp}\ z_1 \cup z_2 \setminus (y_1 \cup y_2);\ \text{do}\ []_{i \in I \cup J}\ A_i\ \text{od}\ ]|$$

Resource tools

- Resource accessibility
  - A.cell, gd(A) = lg(A) $\wedge$ g
- Replicated and homonym resources
  - |R.loc|>1, |H.loc|=1
  - Updating mechanisms distinct
  - Not more than one replica at one location
- Mobility – of all resources
- Node failure and maintenance
  - $V=V_{act} \cup V_{maint} \cup V_{failed}$
  - location guard: every involved location $\in V_{act}$

Networks and Energy

- Networks are everywhere
  - need them to work continually and at full capacity
  - i.e.: reliable and available
- Networks are *not static* anymore
  - devices are battery-powered
  - devices have power-hungry features
  - devices need to plug to electricity

Energy (power)

- non-functional property
- addressed together with reliability, security, availability
  - by a network manager
  - at the middleware level

Energy-aware resources

- Energy: consumed or requested
- Data and storing data
  - Consumes no energy (assumption)
- Code
  - P – amount of power that code requests for being executed
  - **(a, loc, A, P)**
  - **A.P**

Distinct types of energy aware resources

- Code needs hardware to execute on
- Hardware needs power supply
  - From battery or electric socket
- Software and hardware resources
  - Energy requesters/consumers
  - Latter have battery and electric socket connection
- Electrical sockets
  - Energy suppliers

Electrical socket

- ES = |[exp (E, loc, Boolean, T)]|
- Socket is free to charge
  - E.val = T
- Socket already charges a device
  - E.val = F
- Homonym E allowed, replicated E not
  - |E.loc| = 1

Hardware resource

```
HW = |[exp {(B,,,0), (charge,,,F)};
        imp E;
        do charging::
                charge.val ∧ B.val <BMAX →
                B.val := B.val + E_unit
           [] plug:: plug.loc=E.loc →
                charge.val := ¬ charge.val;
                E.val := ¬ E.val
           [] skip:: skip
           [] act
        od
      ]|
```

Hardware resource, cont.

- **act::** if charge.val then A

  else

  gd(A) $\wedge$ B.val > min + A.P $\rightarrow$

  A.body; B.val := B.val – A.P

  fi

- *Assumptions*
  - *min >= skip.P + plug.P + charging.P*
  - *A.P < BMAX*

Connecting the resources

- Data and code cannot exist unless stored on hardware
  - |[imp B, charge, z; do A_i od]| || HW
  - we check there is a local hardware:

    $\{B, charge\} \subseteq (A_i.loc).var \rightarrow$
- Hardware consumes energy when executing code:

  if charge.val then A_i

  else

  $gd(A_i) \wedge B.val > min + A_i.P \rightarrow$

  $A_i.body; B.val := B.val - A_i.P$

  fi

Resources and locations

- Nodes α in (V, Edges) are hardware devices
  - Can be mobile…
- Location: any spatial coordinate where computation, communication can happen
  - E.g.: all physical space in a cellular network
  - Location is now fixed!
  - (V, Edges) is a reference system for mobile resources
    - Infrastructure network

Example

- *Suppose you walk in Vigeland park*
- *You pass a restaurant*
  - *Get the daily menu and price as SMS on the phone*
- *You pass through the statues*
  - *Can get a SMS or sound file or a video about that statue*
  - *Enough memory to get the info?*
  - *Enough power to watch the video?*

Example (cont.)

- *If not enough power, check back the restaurant*
  - *They have power supplies (available?)*
- *With the phone charged, you can check the statue video*
  - *And the statue itself*
  - *Get other videos*

2 types of networks

- Electricity network
  - Provides energy
  - Contains the electrical sockets or *electricity resources*
  - Typically stationary
- Resource network
  - Consumes energy
  - Software resources and hardware devices
  - Can be mobile
- Both networks are location aware

Unitary approach in MIDAS

- We model various types of resources
  - Data, code, hardware, electricity
- Resource locations interrogated
  - Data, code, remaining power
- Electricity resources interrogated
  - Data, code, devices co-located with them
  - Useful for context-aware computing (avoid power supplies that are crowded)

Formalism

- Conservative extensions
  - Action systems → MIDAS → energy-aware MIDAS

  ⇒We can reuse techniques
    - Priorities of code/hardware
    - B-method tools
- Energy-aware specifications **refine** the energy-transparent ones

Conclusions

- We proposed a modeling framework for energy-aware resources
  - Allows for measuring energy
  - Suggests SW/HW model distinction
  - Gives a new approach for locations
    - Suggests definition of location clusters
- Further work
  - Strategies for specifying code or hardware consuming the least amount of energy

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CSP

- For modeling concurrent systems
- CSP system = a set of processes
  - Each process has its own interface of events and typed channels
  - Events: for process synchronization
  - Channels: for data communication among channels
- Operational semantics
  - Transition rules for each process type
- Denotational semantics
  - Traces (special sequences of events)

Constructing CSP systems

- CSP specifications
  - Describe the allowed behavior of the processes
- CSP implementations
  - Describe the actual behavior of the processes
- Trace-based refinement
  - Ensure that every trace of an implementation is also a trace of the corresponding specification

CSP Extensions

- For hybrid systems and for time-dependent systems
  - Timed CSP: continuous model of time
  - Tock – regularly marks the passing of time
    - Tools
- Software tools
  - Model checker FDR
  - Animator ProBE

CCS

- Also for modeling concurrent systems
- CCS system: parallel composition of processes
  - They can synchronize and communicate by using pre-established links
- π-calculus
  - CCS extension
  - Links can communicate values AND links
    - First technique for modeling mobility

CCS and π-calculus: semantics and constructing systems

- Operational semantics
  - Labeled transition systems
  - Many variants
- Constructing systems
  - We can develop abstract and concrete models
  - Bisimilarity (weak and strong)
    - Behavioral equivalence
    - Ensures that 2 models correspond to each other

Extensions and software for π-calculus

- Many extensions
  - Exp: OO based on a type system in terms of sorts
- Software tools
  - Model checker Mobility WorkBench
    - Verifies also bisimilarity properties
  - Programming languages based on π-calculus
    - Pict, Nomadic Pict, Piccola
- Semantic model for concurrent calculus

Ambient calculus

- For modeling computations over Internet
- Ambient
  - Administrative domain in Internet
  - Place where various computations take place
  - Can contain sub-ambients or be contained in a parent-ambient
  - Sibling ambients can communicate locally
  - Mobility – most important feature
    - Need to cross barriers
    - Stepwise

Ambient calculus: semantics and analysis methods

- Operational semantics
- Can express both π-calculus as well as λ-calculus
- Expressing properties
  - Communication and mobility types
    - Ensure that communication is correct (well-typed)
    - Mobility can be restricted if desired
  - Decidable modal logic
    - Model checking for various process properties
  - (More complex) modal logic for mobility
    - Can express time and space
    - Mobility: change of spatial configurations over time

UNITY

- State-based formalism for modeling distributed systems
- System state
  - Described by variables
  - Modified by conditional assignments
  - An assignment can be chosen for execution only when its guarding condition holds
  - Choosing between several executable assignments is weakly fair
- UNITY system: more programs
  - Homonym variables are shared
  - Assignments can execute synchronously or asynchronously

UNITY: semantics and constructing systems

- Denotational semantics
  - Transition systems
- Reasoning about programs
  - Temporal logic: safety and liveness properties can be expressed and proved wrt the UNITY models
- Structuring techniques
  - Union and superposition refinement

Mobility in UNITY

- Mobility
  - Mobile UNITY: specialization of UNITY
  - Programs have “location” variables
  - Specialized conditional assignments execute as long as their conditions hold
  - centralized “Interactions” section coordinates the programs
    - The section contains the sharing and synchronization conditions
  - Dynamic style of computing

Context in UNITY

- Context-UNITY
  - Specialized version of Mobile UNITY
  - Models environment-sensitive applications
  - “Interactions” section replaced by several “Context” sections
    - One per program
    - Contain coordination rules
  - Very flexible systems can be modeled

Z

- Oldest state-based formalism
- Modeling systems based on abstract data types
- Z-System: variables and operations
  - Variables have types, invariants and initializations
  - Operations are expressed as predicates describing the system state before and after the operation
  - Z-Schemas (syntactical structures)

Semantics and analysis in Z

- Semantics based on values
  - Schema S corresponds to θS
  - θS – characteristic binding of S
    - Each declared component is associated with its current value
- Proofs and refinements
  - Based on set theory and logics

Extensions of Z

- Timed refinement calculus
  - Z extended with total continuous functions of time
- Object-Z
  - Enhances the structuring of Z specifications
  - Class-schema contains all the schemas concerning an abstract data type
  - Refinement of classes with simulation techniques
  - Reference-based semantics
    - Variables refer values instead of directly representing them
  - Extra semantics in terms of *transition systems*
- Combinations
  - Timed refinement calculus and Object-Z
  - Object-Z and CSP (and their timed extensions)

B

- State-based formalism for
  - Modeling, refinement, validation, and implementation of software systems
- B specification unit: abstract machine
  - Variables and operations that can evaluate and modify variables
  - Invariants:
    - Constrain variables
    - Must be preserved by the operations

Modularity, validation and refinement in B

- Fundamental features of B
- Modularity
  - System: a collection of machines that are independently developed
- Refinement
  - Algorithmic or data refinement
- Validation
  - Discharging the proof “obligations” generated in the refinement process

B supported by software tools

- Validation
  - Highly automated due existing associated tools (theorem provers)
    - Atelier-B and B Toolkit
  - Many proof obligations are discharged automatically by the software
  - The remaining obligations can be interactively proved
  - When all the proof obligations are discharged code can be generated in C or ADA

Semantics and extensions in B

- Semantics
  - Based on an extension of the weakest-precondition calculus, set theory, logics
- Extensions
  - Distributed and reactive systems (Event-B)
  - Complex systems (software and hardware)

Conclusions

- We have plenty of formal tools to choose from
  - They can model ≈ anything
  - How to choose?
    - Integrate formal methods? (UML?)
  - Do they scale?
  - Do they have associated tools?

Motto

- **The sciences do not try to explain, they hardly even try to interpret, they mainly make models.**

John von Neumann

Material

- http://web.abo.fi/~lpetre/

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