Cadena: An Integrated Development, Analysis, and Verification Environment for Component-based Systems

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presented by Jaroslav Ševčík
Overview

- Goal – use formal methods in software development process
- Cadena – framework for
  - dependency analysis with varying levels of precision.
  - extracting checkable models from component specification.
- Based on CORBA component model
- Used for real-time systems
- Targetted at all mission/safety-critical systems
Formal methods

- Reasoning about various aspects of a program
- Uses mathematical logic for specifications
- Proving program invariants, preconditions, postconditions

Types of formal methods
- Light-weight – unsound and incomplete
- Medium-weight – sound, but incomplete
- Heavy-weight – sound and complete

Successful applications in hardware
- Do not scale well enough for software
Automated Theorem Proving

- Heavy-weight technique
- Input: (annotated) program
- Verification condition generated:
  - from the code, e.g.
    - For `x.field = 0;` we have to prove that `x ≠ 0`.
    - `a[i] = 0;` implies `i ≤ a.length`.
  - from the annotations, i.e. class invariants, method pre- and post-conditions etc.
- Generate theorems using Hoare logic, weakest precondition etc.
- The verification condition then checked using an automated theorem prover.
Usage of ATP

- ACL2 theorem prover (parts of AMD K7 design)
- ESC/Java
  - unsound and incomplete
  - ... e.g. loops, guessing object invariants, or axiomatization of floating point numbers
  - More like type checking, but uses heavy-weight tools
  - “How to shoot sparrows with cannons”
- Spec# - formal specification for C#
  - Similar to ESC/Java, but is sound and under some assumptions also complete
  - Powerful precondition, postcondition and invariant inference
Model checking

- Light-weight technique
- State-space exploration
- Based on a program abstraction (model)
  - Finite size
  - Reasonably large state space
- Usually used for
  - Protocols
  - Hardware
  - Concurrent programs
SPIN

- SPIN is the most widely used model checker
- Uses PROMELA language
- SPIN model consist of
  - type declarations
  - channel declarations
  - variable declarations
  - process declarations
- No unbounded data, channels or processes
Type declarations

- Basic types: `bool`, `bit`, `byte`, `short`, `int` and arrays:

```c
bool flag = 1; /* declaration */
byte counter[30];
flag = 0; /* assignment */
```

- Default value is always 0.

- Records:

```c
typedef record {
    short f1;
    byte f2;
}
Record rr;
rr.f1 = ..;
```
Statements

- Two types of statements:
  - **Executable** – can be executed immediately
  - **Blocking** – cannot be executed

- **Assignment** is always executable

- **Expression** is also a statement
  - and is executable only if it evaluates to non-zero:
    - $2 < 3$ always executable
    - $x < 27$ executable if $x$ smaller than 27

- **skip** statement is always executable

- **assert** statement is also always executable
Processes

Process declaration and creation:

```plaintext
proctype Foo(byte x)
{
    ...
}

init {
    int pid2 = run Foo(8);
}
```

Processes are:

- executed concurrently
- scheduled non-deterministically
- interleaved (no two statements execute at the same time)
Mutual exclusion

```c
bool x, y, t;

proctype A()
{
    x = 1;
    t = 1;
    (y == 0 || t == 0);
    /* critical section */
    x = 0 }

proctype B()
{
    y = 1;
    t = 0;
    (x == 0 || t == 1);
    /* critical section */
    y = 0 }

init
{
    run A(); run B() }
```
How to use SPIN to check the correctness for us?

Use a variable that gets incremented and decremented in every critical section:

```c
mutex++;  
mutex--;  
```

... and run a process that will guard the variable:

```c
active proctype monitor() {
    assert (mutex != 2);
}
```

If the program is wrong the assert in the sequence

```c
mutex++; /* <- P0 */  
mutex++; /* <- P1 */  
assert (mutex != 2); /* process monitor */
```

will fail!
Atomicity

- All statements are atomic

- `atomic{stmt1; stmt2; ...; stmtn}` statement can be used to define atomic sequences, e.g. atomic test and set:

  ```
  atomic{ flag != 1; flag = 1 }
  ```

- No pure atomicity (even if statement $i$ is blocked, all statements $1 \ldots i$ will be still executed).

- For deterministic sequences use `d_step` instead of `atomic`
  - No intermediate states are generated.
  - Reduces state space.
  - Possibly blocking or non-deterministic statements cause run-time errors!
Non-deterministic choice

- If statement:

```c
int a = 0, x = 1, y = 1;
proctype A() {
    if
    :: x == 1 -> a = a + 1
    :: y == 1 -> a = a - 1
    fi
}
```

- At the end $a = 1$ or $a = -1$, SPIN will make a non-deterministic choice.

- If $x \neq 1$ and $y \neq 1$, the statements will block.

- **do** statement similar to **if**

- Loops until an explicit **break** statement
Communication

- Channel declaration:

  ```
  chan c = [2] of {bit}
  ```

- The number denotes the size of the message queue.

- Sending a message – using `!` operator

  ```
  c ! 1;
  ```

- If channel full ⇒ the send statement will block

- Receiving a message:

  ```
  c ? 1;
  c ? x;
  ```

- If channel empty or the constant is not the same ⇒ the receive statement will block
dSPIN

- Dynamic extension to SPIN
- Adds to the language
  - Memory management (`new` and `delete`)
  - Functions (`function`)
  - Pointers (`&` operator, type)
  - Function pointers (`ftype` type)
  - Local scoping
  - Garbage collection
- Simplifies object-oriented specification
Bandera

- Model-checking framework for Java
- Program states typically very large
- Bandera uses
  - **Slicing** to eliminate the code that does not relate to the verified property
  - **Data abstraction** to decrease state size
    - E.g. vector can be often abstracted by a small set \{ItemInVector, ItemNotInVector\}.
- Its back-end supports various model-checkers (SMV, SPIN etc.)
Cadena architecture I

- Centered around CORBA middleware
- Components described using
  - CORBA IDL
    - Interfaces, data types and components
  - Cadena Assembly Description (CAD)
    - Static component allocation and configuration policy
  - Cadena Property Specification (CPS)
    - Dependencies and behaviors
- Correctness Properties
  - …using Linear Temporal Logic
Cadena architecture II

Outputs:
- Generated code:
  - Stubs
  - Skeletons
  - Implementation (from IDL)
  - System assembly (from CAD)
- dSPIN model

- Offers the possibility of graphical views
- … and spreadsheet views
Cadena methodology

Development steps:

1. Load library of components and their CPS
2. Define new components and CPS
3. Define CAD to specify connections between components
4. Examine dependencies using the graphical viewer
5. Attach non-functional aspect specification
6. Specify global correctness properties
7. Generate transition system model and model-check correctness properties
8. Revise system using feedback from analysis tools
Case study

- Avionics software based on Boeing Bold Stroke architecture
- The software manages
  - Cockpit displays
  - Navigation and tactical sensors
  - Weapon deployments
- Periodic and aperiodic processing
- Thousands of operating modes
- Technologies: CORBA, C++
Example

- Cadena system is demonstrated on a simple running example

- Simple avionics system that shows steering cues on a pilot’s display

- Pilot can choose one of the modes:
  - *Tactical* display – mission objectives
  - *Navigation* display – navigation objectives
    - Derived from navigation points entered by navigator
Components in the avionics system:

- GPS component, data sampled at a rate 20Hz
- The data passed to an intermediate modal component AirFrame
- NavSteering and TacticalSteering – modal components producing data for Display component based on data from the AirFrame component
- Navigator - polls for input at a rate 5Hz and pushes them to NavSteeringPoints
- NavSteeringPoints are used by the NavSteering component
Simple avionics system - diagram
Control-push data-pull

- Data transferred in two step process:
  1. Data producer publishes `DataAvailable` event
  2. Upon receiving the event data consumer calls `get data` accessor method

- Advantage – no thread blocking $\Rightarrow$ less opportunities for deadlock

- The `DataAvailable` notification sent through an event connection

- The data can be then retrieved through an interface connection
LazyActive component

- Example: *AirFrame* component
- *AirFrame* does not fetch data from *GPS* immediately
- …it only sets *dataStatus* to *stale* and sends the *DataAvailable* event
- When then queried for data it checks the status
  - If *dataStatus* = *stale* it queries *GPS* for the data, sets status to *fresh* and returns the data
  - If *dataStatus* = *fresh* it just returns the (fresh) data
module modalsp {

  interface ReadData {
    readonly attribute any data;
  };

  eventtype DataAvailable {
  }

  enum LazyActiveMode {stale, fresh};

  component LazyActive {
    provides ReadData dataOut;
    uses ReadData dataIn;
    publishes DataAvailable outDataAvailable;
    consumes DataAvailable inDataAvailable;
    attribute LazyActiveMode dataStatus;
  }

};
Cadena Assembly Description

```plaintext
system ModalSPScenario {
    import cadena.common, cadena.modalsp;

    Rates 1, 5, 20;
    Locations 11, 12, 13;

    Instance AirFrame implements LazyActive on #LALoc {
        connect this.inDataAvailable
to GPS.outDataAvailable runRate #LARate;
        connect this.dataIn to GPS.dataOut
    }

    Instance TacticalSteering implements Modal1 on 12 {
        connect this.inDataAvailable
to AirFrame.outDataAvailable runRate 5;
        connect this.dataIn to AirFrame.dataOut;
    }

    ...
}
```

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component LazyActive {
    mode dataStatus;
    dependencydefault == none;

dependencies {
    case dataStatus of {
        stale: inDataAvailable -> outDataAvailable;
        dataOut.get_data(); -> dataIn.getData();
        fresh: inDataAvailable -> outDataAvailable;
    }
}

behavior { ...
    ...
}
Dependency analysis

The steps for creating and refining dependency information:

1. Use global dependence default (every input and output port can be connected)
2. Specify dependency without modal behavior
3. Refine by considering modes
4. Refine by behavioral descriptions (which captures control-flow)

Basic notions of dependency:

- Inter-component dependencies – interface and event dependencies
- Intra-component dependencies – trigger dependency
Dependency information usage

- Some properties can be devised automatically using the dependency information:
  - Rate assignment to the ports
    - The rates can be distributed through the system
    - If more than one rate identified $\Rightarrow$ the higher one is used
  - Distribution determination
  - Synchronous dispatch optimization
    - Every non-correlated? co-located remote event delivery can be reduced to a synchronous call
Component modeling

Straightforward translation from behaviors:

```c
ftype Ref_NavSteering_dataIn1_getData;
ftype Ref_NavSteering_update;

function Fun_NavSteering_source1 (mtype t) {
    if :: NavSteering_componentState == enabled ->
        NavSteering_internalData = Ref_NavSteering_dataIn1_getData();
        Ref_NavSteering_update(NavSteering_DataAvailable)
    :: else
    fi
}
```
Modeling Middleware

- Event publication
  - ...is achieved by placing function reference and event type to the channel thread process.

- Thread services
  - Rate monotonic scheduling:
    - Higher rate $\Rightarrow$ higher priority
  - Encoded using guarded actions

- Events modeled using rate groups and interfaces modeled using direct function calls?
Modeling a rate group thread:

```plaintext
proctype RateGroup_1Hz () {
    ftype f;
    mtype m;
    ...
    do
        :: skip ->
            S_timeout?b;
        ...
    do
        :: Rate1_queue?[f, m] -> Rate1_queue?f(m); f(m)
        :: else -> break;
    od
    od
}
```
function Fun_NavSteering_switch_getData () : int {
    atomic {
        P <= 1 ->
            P = MaxPriority
    }
    return NavSteering_componentState;
}

active proctype PriorityHandler() {
    do
        :: timeout -> d_step {
            if
                :: P > 0 -> P = P - 1;
            :: else
                fi
        }
    od
}
Simulating time

- No explicit notion of time
- Only the relative rate is preserved:
  - Take $m$ as least common multiple of all rates in the system
  - Instantiate a counter $t$ counting from 0 to $m - 1$ in a loop
  - Issue a timeout event for a rate $k$ if $t \mod m/k = 0$.
  - Can be scaled down by GCD of all the rates.
- Modeled using rendezvous channels in SPIN (i.e. channels with queue size 0).
- Each rate group has one channel and one SPIN process for the timeout events dispatch
Timer for 5, 10, 15Hz

```c
proctype Timer() {
    int t = 0;
    do
        :: (t >= 6) -> t = 0
        :: (t < 6) ->
            if
                :: (t \% 2) == 0 -> S_timeout15!1;
            :: else
                fi;
            fi;
        if
            :: (t \% 3) == 0 -> S_timeout10!1;
        :: else
            fi
        if
            :: (t \% 6) == 0 -> S_timeout5!1;
        :: else
            fi;
        t = t + 1
    od;
}
```
Property Specification

- No explicit examples
- User can reason about:
  - call or return from a component method
  - publication or consumption of an event
  - values of component modes
- Observations can be qualified by
  - Component instance
  - Parameter and return values
  - Component ports
  - Rate groups
- Timeedit tool for visual editing of time properties
Experience

- Without enforcing the rate monotonic scheduling check aborted with
  - 26 million states
  - 1 GB RAM consumed
- With rate-monotonic scheduling:
  - 1.4 million states
  - 130 MB RAM
  - running time ≤ 1 minute.
Pros and Cons

Advantages:

- Formal guarantees of system properties
- Incremental dependency analysis

Disadvantages:

- Does not seem to scale well
- Non-functional modelling non-trivial (it is not clear has to be done manually and what is done by the tool)
- Oriented on very static systems
- Overall too tailored to Bold Stroke type systems