Computational Models for Embedded Systems

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Lecture 2: Model checking

Software Systems Verification and Validation

"Tell me and I forget, teach me and I may remember, involve me and I learn."

(Benjamin Franklin)

Grading

https://www.cs.ubbcluj.ro/files/curricula/2025/syllabus/IS_sem3_MME8026_en_avescan_2025_9498.pdf

- To be Updated about the Grading (after this first lecture)

Research
- Dissertation Thesis
- Internship in Specialization

~~To be UPDATED?~~
~~10-Oct-2025~~

Final Grade

G=50%Seminar + 50%Exam
(10%Quiz+40%Report)

- Final Grade = 50% Seminar (=10%*Pb+20%*MC + 20%*FSM) + 50% Exam (=10%Quiz+40%*ReportSLR)
- Conditions to participate at the final exam
  - There is no restriction regarding the participation at the written examination regarding obtained marks Pb, MC, FSM.
- Pb, MC, FSM work may not be redone in the retake session.
- Conditions to pass/complete the CMES discipline:
  - Final Grade >= 5 final grade.

Gamify Your Class

http://www.techedupteacher.com/gamify-your-class-level-i-xp-grading-system-2/

	Side Quests (Lab projects)	Epic Quests (Final exam)
Normal session	Pb + MC + FSM 1500 XP	Up to 1500 XP (Quiz 300 + ReportSLR 1200 X
Retake session	Received during Normal session Points obtained in the didactic activity period (labs and seminar and bonus activity cannot be redone in the normal/retake session).	Up to 1500XP

Final exam – you must come (be present) to the final exam in order to compute the grade!

Outline

Model checking

- System verification
- Model checking
- Transition system
- Linear-Time Properties
- Linear-Time Logic
- Computation Tree Logic

Spin Model Checker

- Spin
- Promela Model
  - Statements
  - Examples
- Concurrency and Interleaving Semantics
  - Examples
- Linear Temporal Logic
  - Examples
- Channels in Promela
  - Examples
- JSpin

System verification (1)

Information and Communication Technology (ICT)

correctness

money

safety

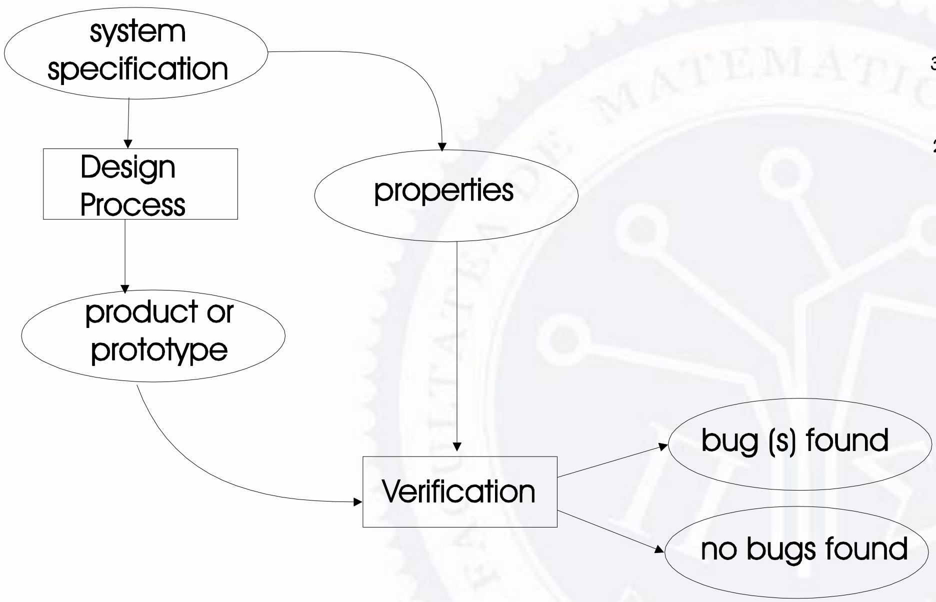
Reliability of the ICT systems

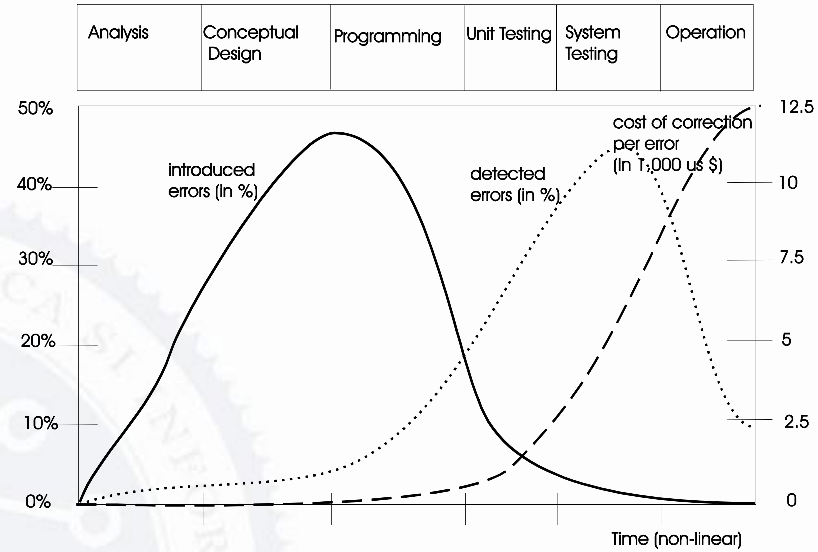
Interactive systems
- concurrency & nondeterminism

Pressure
- to reduce system development time

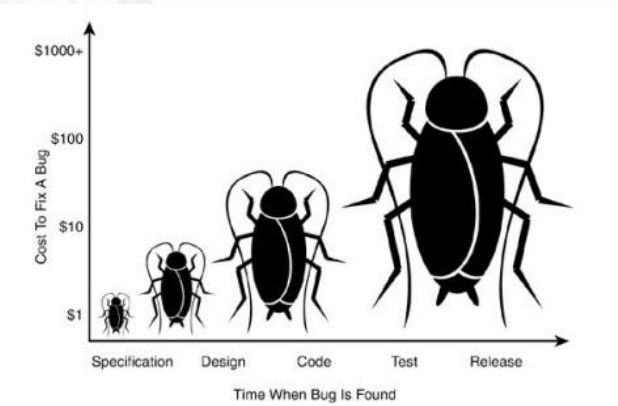
System verification

System verification (2)





Catching software errors
the sooner the better



- Software verification
  - Review
    - No concurrency defects
    - Algorithm defects
  - Testing
    - Exhaustive testing?
    - When to stop?

System verification (3)

Formal methods

- To establish system **correctness** with **mathematical rigor**.
- To facilitate the **early** detection of defects.

- Mechanical Engineering is like looking for a black cat in a lighted room.
- Chemical Engineering is like looking for a black cat in a dark room.
- Software Engineering is like looking for a black cat in a dark room in which there is no cat.
- Systems Engineering is like looking for a black cat in a dark room in which there is no cat and someone yells, "I got it!"

Model checking

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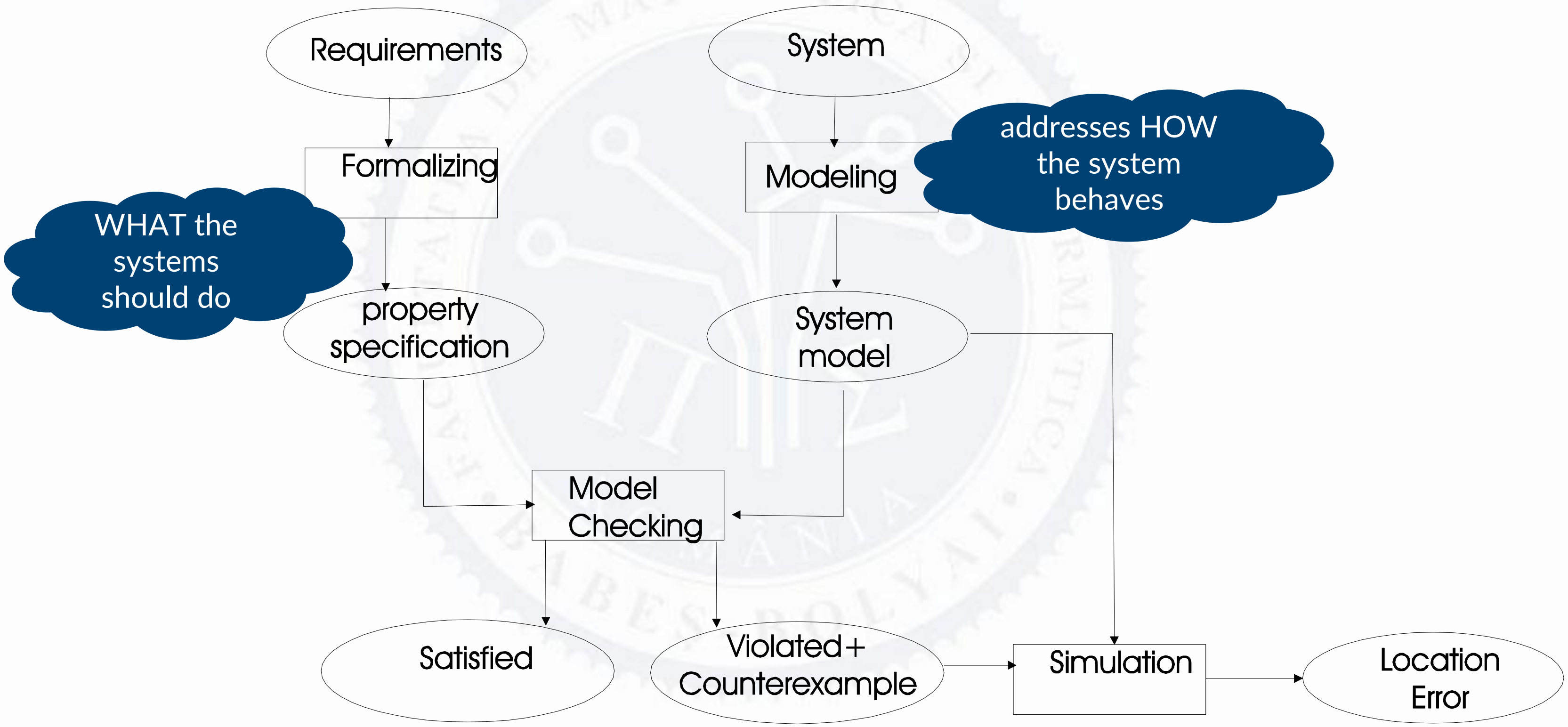
Model checking (1)

Formal methods

- More time and effort spend on verification than on construction
  - in software/hardware design of complex systems.
- The role of formal methods:
  - To establish system correctness with mathematical rigor.
  - To facilitate the early detection of defects.
- Verification techniques
  - Testing – small subset of paths is treated
  - Simulation - restrictive set of scenarios in the model
  - Model checking - exhaustive exploration
- **Remark.** Any verification using **model-based techniques** is only as good as the model of the system.

Model checking (2)

Approach



Remark. Any verification using **model-based techniques** is only as good as the model of the system.

Model checking (3)

Characteristics

- Model checking is an automated technique that, given a finite-state model of a system and a formal property, systematically checks whether this property holds for (a given state in) that model.
- The model checking process
  - Modeling phase
    - model the system under consideration
    - formalize the property to be checked.
  - Running phase
  - Analysis phase
    - property satisfied?
    - property violated?

Model checking (4)

Strengths	Weaknesses
• General verification approach • Supports partial verification • Provides diagnostic information • Potential “push-button” technology • Increasing interest by industry • Easily integrated in existing development cycles	• Appropriate to control-intensive applications • Its applicability is subject to decidability issues • It verifies a system model • Checks only stated requirements • Suffers from the state-space explosion problem • Requires some expertise

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Transition system (1)

Definition

- Transition systems - used in computer science as models to describe the behavior of the systems.
- Transition systems - directed graphs:
  - Nodes - represent states;
  - Edges - model transitions, i. e. state changes.
- A Transition System (TS) is tuple (S, Act, $\rightarrow$, I, Ap, L), where
  - S is a set of states,
  - Act is a set of actions,
  - $\rightarrow \subseteq S \times Act \times S$ is a transition relation,
  - $I \subseteq S$ is a set of initial states,
  - AP is a set of atomic propositions, and
  - $L : S \rightarrow 2^{AP}$ is a labeling function.
- TS is called finite if S, Act and AP are finite.

Transition system (2)

Remarks

- Intuitive behavior of a transition system
  - Initial state $s_0 \in I$
  - Using the transition relation $\rightarrow$ the system evolves
  - Current state s, a transition $s \xrightarrow{\alpha} s'$ is selected *nondeterministically*
  - The selection procedure is repeated and finishes once a state is encountered that has no outgoing transitions.
- The labeling function L relates a set $L(s) \in 2^{AP}$ at atomic propositions to any state s. $L(s)$ intuitively stands for exactly those atomic propositions $a \in AP$ which are satisfied by state s.
- Given that ϕ is a propositional logic formula, then s satisfies the formula ϕ if the evaluation induced by $L(s)$ makes the formula ϕ true.

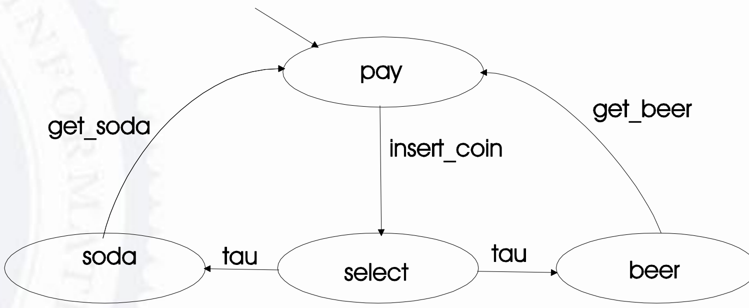
  $s \models \phi$ iff $L(s) \models \phi$.

Transition system (3)

Example

Beverage Vending Machine

- $S = \{pay, select, soda, beer\}$, $I = \{pay\}$
- $Act = \{insert\_coin, get\_soda, get\_bear, \tau\}$
- Example transitions: $pay \xrightarrow{insert\_coin} select$, $beer \xrightarrow{get\_beer} pay$
- Atomic propositions depends on the properties under consideration.
  A simple choice - to let the state names act as atomic propositions, i. e. $L(s) = \{s\}$.
  "The vending machine only delivers a drink after providing a coin."
  $AP = \{paid, drink\}$, $L(pay) = \emptyset$, $L(soda) = L(beer) = \{paid, drink\}$, $L(select) = \{paid\}$.



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Linear-Time Properties

- **Deadlock** – if the complete system is in a terminal state, although at least one component is in a (local) nonterminal state.
    - A typical deadlock scenarios occurs when components mutually wait for each other to progress.

- **Safety properties** = “nothing bad should happen”.
    - The number of inserted coins is always at least the number of dispensed drinks.
    - A typical safety property is deadlock freedom
    - Mutual exclusion problem – “bad” = more than one process is in the critical section

- **Liveness properties** = “something good will happen in the future”.
    - Mutual exclusion problem – typical liveness properties assert that:
        - (eventually) – each process will eventually enter its critical section
        - (repeated eventually_ = each process will enter its critical section infinitely often
        - (starvation freedom) – each waiting process will eventually enter its critical section

- Remark
    - **Safety properties** - are violated in finite time (a finite system run)
    - **Liveness properties** – are violated in infinite time (by infinite system runs)

Temporal Logic

- **Propositional temporal logics** - extensions of propositional logic by temporal modalities.

- The elementary temporal modalities that are present in most temporal logics include the operators
  - “**eventually**” (eventually in the future) -
  - “**always**” (now and forever in the future –

- The nature of time in temporal logics can be either **linear** or **branching**.

- The adjective “temporal”
  - specification of the relative order of events
  - does not support any means to refer to the precise timing of events

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Linear-Time Logic (1)

Syntax of LTL

- Construction of LTL formulae in LTL - ingredients:
  - atomic propositions $a \in AP$, (stands for the state label a in a transition system)
  - boolean connectors like conjunction $\wedge$ and negation $\neg$,
  - basic temporal modalities "next" $\bigcirc$ and "until" $\bigcup$.
- LTL formulae over the set AP of atomic proposition are formed according to the following grammar:
  $\varphi ::= true | a | \varphi_1 \wedge \varphi_2 | \neg\varphi | \bigcirc \varphi | \varphi_1 \bigcup \varphi_2$, where $a \in AP$.

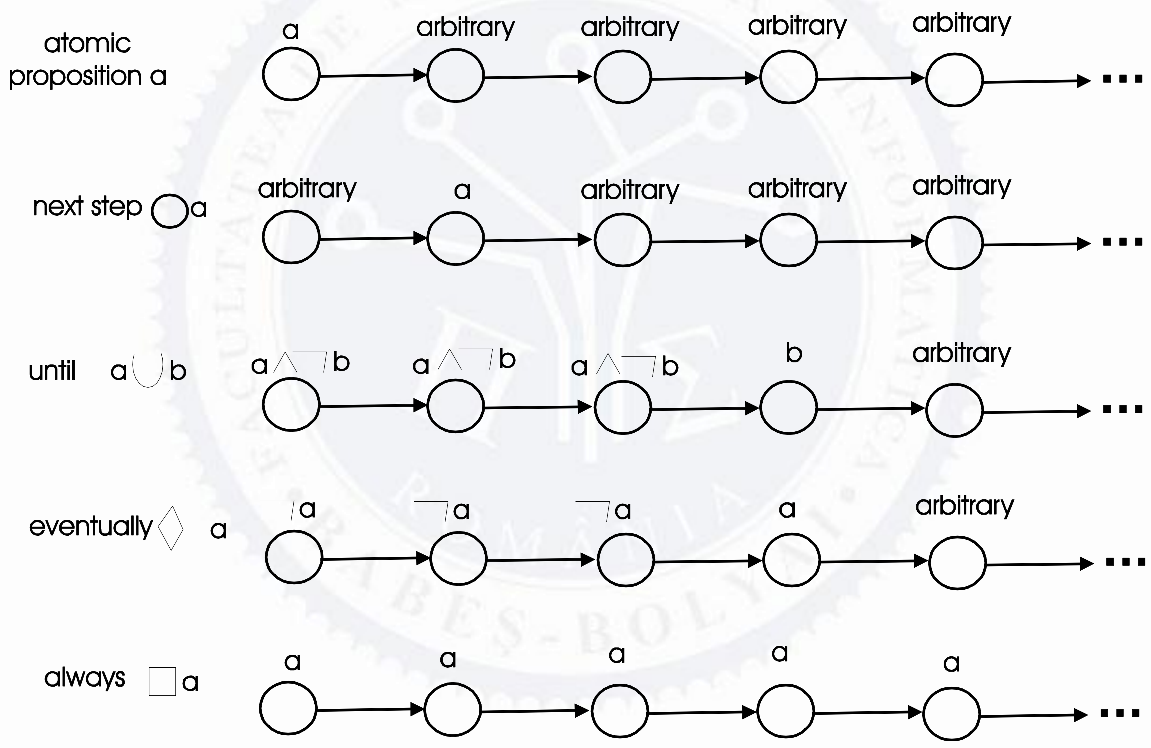
Linear-Time Logic (2)

LTL temporal modalities

- The until operator allows to derive the temporal modalities $\Diamond$ ("eventually", sometimes in the future) and $\Box$ ("always", from now on forever) as follows:
  - $\Diamond\varphi = \text{true} \bigcup \varphi$.
  - $\Box\varphi = \neg\Diamond\neg\varphi$.
- By combining the temporal modalities $\Diamond$ and $\Box$, new temporal modalities are obtained:
  - $\Box\Diamond\varphi$ - "infinitely often φ."
    at any moment j there is a moment i $i \geq j$ at which an a state is visited
  - $\Diamond\Box\varphi$ - "eventually forever φ."
    from some moment j on, only a-states are visited.

Linear-Time Logic (3)

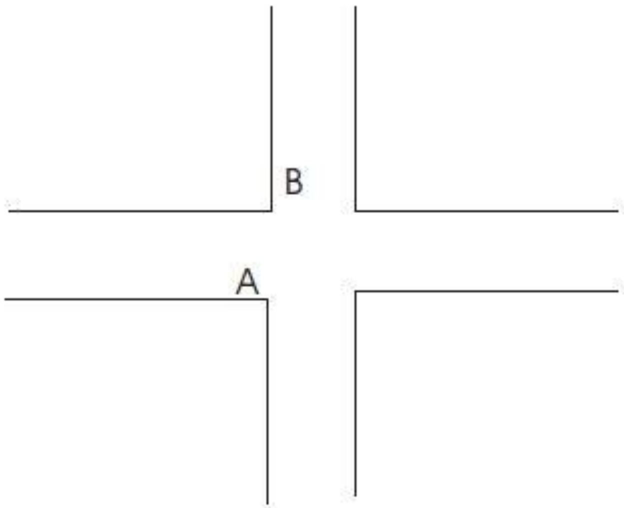
Intuitive meaning of temporal modalities



Linear-Time Logic (4)

LTL semaphore example

- $\Box(\neg(A = green \wedge B = green))$
  - A and B can not be simultaneously green.
- $\Box(A = yellow \rightarrow A = red)$
  - If A is yellow eventually will become red.
- $\Box(A = yellow \rightarrow \bigcirc(A = red))$
  - If A is yellow then it will be red into the next state.
- $\Box(\neg(B = green) \bigcup (A = red))$
  - B will not be green until A changes in red.



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Computation Tree Logic (1)

Syntax of CTL

- Construction of CTL formulae:
  - as in LTL by the next-step and until operators,
  - must be not combined with boolean connectives
  - no nesting of temporal modalities is allowed.
- CTL formulae over the set AP of atomic proposition are formed according to the following grammar:
  $\phi ::= \text{true} \; |a|\phi_1 \wedge \phi_2|\neg\phi|\exists\phi|\forall\phi$, where $a \in \; AP \; and \; \varphi$ is a path formula.
- CTL path formulae are formed according to the following grammar:
  $\varphi ::= \bigcirc\phi|\phi_1 \bigcup \phi_2$, where $\phi, \phi_1 and \phi_2$ are state fromulae.

Computation Tree Logic (2)

CTL - state and path formulae

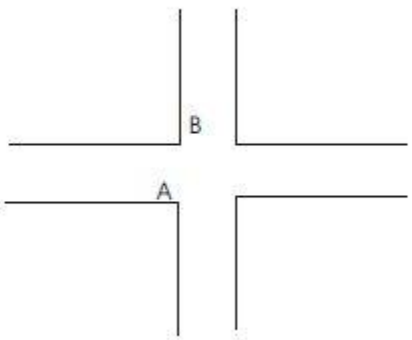
- CTL distinguishes between state formulae and path formulae:
  - State formulae express a property of a state.
  - Path formulae express a property of a path, i.e. an infinite sequence of states.
- Temporal PATH operators $\bigcirc$ and $\bigcup$
  - $\bigcirc\phi$ holds for a path if ϕ holds in the next state of the path;
  - $\phi \bigcup \psi$ holds for a path if there is some state along the path for which ψ holds, and ϕ holds in all states prior to that state.
- Path formulae $\Rightarrow$ state formulae by prefixing them with
  - path quantifier $\exists$ (pronounced "for some path");
    $\exists\phi$ - holds in a state if there exists some path satisfying ϕ that starts in that state.
  - path quantifier $\forall$ (pronounced "for all paths".)

    $\forall\phi$-holds in a state if all paths that start in that state satisfy ϕ.

Computation Tree Logic (2)

CTL – semaphore example

- $\forall\Box(B = yellow \rightarrow \forall\bigcirc(B = red))$.
  - If B is yellow, it will become (sometime in the future) red.



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Spin Model checker

Spin

- Developed at Bell Labs.
- In 2002, recognized by the ACM with Software System Award.
- SPIN (= Simple Promela Interpreter)
- is a tool for analyzing the logical consistency of concurrent systems
- Concurrent systems are described in the modelling language called Promela (= Protocol/Process Meta Language)

Promela

- Promela (= Protocol/Process Meta Language)
- allows for the dynamic creation of concurrent processes.
- communication via message channels can be defined to be
  - synchronous (i.e. rendezvous),
  - asynchronous (i.e. buffered).

http://spinroot.com/
Installation JSpin (See Teams Files-Lecture02)

Promela Model

- Promela model consist of:
  - type declarations
  - channel declarations
  - variable declarations
  - process declarations
  - **[init process]**
- A process type (**proctype) consist of**
  - a name
  - a list of formal parameters
  - local variable declarations
  - Body

- A process
  - is defined by a **proctype definition**
  - executes concurrently with all other processes, independent of speed of behaviour
  - communicate with other processes
    - using global (shared) variables
    - using channels
- There may be several processes of the same type.
- Each process has its own local state:
  - process counter (location within the **proctype)**
  - contents of the local variables

Promela Model - Statements

- The body of a process consists of a sequence of statements.
- A statement is either
  - executable: the statement can be executed immediately.
  - blocked: the statement cannot be executed.
- An assignment is always executable.
- An expression is also a statement; it is executable if it evaluates to non-zero
- The **skip statement is always executable.**
  - “does nothing”, only changes process’ process counter
- A **printf statement is always executable (but is not** evaluated during verification, of course).
- **assert(<expr>);**
  - The **assert-statement is always executable.**
  - If **<expr> evaluates to zero, SPIN will exit with an error, as**
- the **<expr> “has been violated”.**
  - The **assert-statement is often used within Promela models,**
- to check whether certain properties are valid in a state.

Examples (01 Simple Examples)

- ReversingDigits.pml
  - Check
  - Random
- DiscriminantOfQuadraticEquation.pml
  - Check
  - Random
- NumberDaysInMonth.pml
  - Check
  - Random
- MaximumNondeterminism.pml
  - Check
  - Random
  - “Branch 1” and “Branch 2”
- Maximum –second example-MaximumIfElse.pml
  - Check
  - Random
- GCD.pml
  - Check
  - Random
- IntegerDivison01.pml
  - Check
  - Random

- **(Book [2]: pages2-20)**

Concurrency and Interleaving Semantics

02 Concurrency and interleaving semantics

- **(Book [2]: pages 30-41)**

- Promela processes execute concurrently.
  - Non-deterministic scheduling of the processes.
  - Processes are interleaved (statements of different processes do not occur at the same time).
  - exception: rendez-vous communication.
- All statements are atomic; each statement is executed without interleaving with other processes.
- Each process may have several different possible actions enabled at each point of execution - only one choice is made, non-deterministically.
- InterleavingStatements.pml
  - Check
  - Random
  - 6 possibilities of the execution
    - n1,p,n2,q;
    - n1,n2,p,q;
    - n1,n2,q,p;
    - n2,q,n1,p;
    - n2,n1,q,p;
    - n2,n1,p,q.
  - Interactive simulation – Interactive button
- InterferenceBetweenProcesses.pml
- InterferenceBetweenProcessesDeterministic.pml

- **Question (Exam preparation)**
  - What is the difference between **atomic** and **d_step**?
  - Create two examples, one for each of them and clarify the difference.

- Book:
  - Mordechai Ben-Ari_Principles of the Spin Model Checker.pdf

Examples (03 Critical section)

- (Book [2]: pages 45-55)

- CriticalSection_Incorrect.pml
  - both processes – in the critical section
- CriticalSection_MutualExclusion.pml – not satisfied
  - Mutual exclusion – at most one process is executing its critical section at any time.
- CriticalSection_With_Deadlock.pml
  - Blocking on an expression – user Interactive simulation
  - Absence of deadlock – it is impossible to reach a state in which come processes are trying to enter their critical sections, but no process is successful.
- CriticalSection_SolutionAtomic.pml
  - The atomic sequence may be blocked from executing, but once it starts executing, both statements are executed without interference from the other process.

Linear Temporal Logic

- Temporal logic formulae can specify both safety and liveness properties.

- LTL ≡ propositional logic + temporal operators

  `[]P` always P

  `<>P` eventually P

  `P U Q` P is true until Q becomes true

Examples (04 LTL examples)

- (Book [2]: pages 76-80)

- CriticalSection_MutualExclusionLTL.pml
  - LTL formula:
    - []mutex
  - Translate
  - Verify
- CriticalSection_MutualExclusionLTL02.pml
  - LTL formula:
    - []mutex
  - Translate
  - Verify
- CriticalSection_With_Starvation.pml
  - LTL formula:
    - <>csp
  - Translate
  - Acceptance
  - Verify

Channels in Promela 05 Channels

- A channel in Promela = a data type with two operations:
  - send
    - The send statement consists of a channel variable followed by **an exclamation point** and then a sequence of expressions whose number and types match the message type of the channel.
  - receive
    - The receive statement consists of a channel variable followed by **question mark** and a sequence of variables.
- Every channel has associated with it a message type.
- The message type that specifies the structure of each message that can be send on the channel as a sequence of fields).

  Chan ch = [capacity] of {typname, …, typename}
- There are two types of channels with different semantics:
  - Rendezvous channels of capacity 0
  - Buffered channels of capacity greater than 0
- Examples
- **Client-server-channels.plm**

Channels in Promela 05 Channels

- (Book [2]: pages 107-109)

- Rendezvous channel – with capacity 0.
  - The transfer of the message from the sender (a process with a send statement) to the receiver (a process with the receive statement) is synchronous and is executed as a single atomic operation.
- Examples
- **Simple-Rendezvous.pml**
  - The rendezvous is one atomic operation; even if there were other processes, no interleaving could take place between the execution of the send statement and the receive statement.

Traffic-Pedestrian 06 Channels

- Examples

- **PromelaMarryMe_Simple.pml**
- **PromelaMarryMe.pml**
- **traffic_pedestian.pml**

References

- [1] Baier Christel, Katoen Joost-Pieter, Principles of Model Checking , ISBN 9780262026499, The MIT Press, 2008
    - Chapter 1 - System verification, Chapter 2 – Modelling Concurrent systems (page. 19-20), Chapter 3 (page. 89, 107, 120-121), Chapter 5 – Linear Temporal Logic (page. 229-233), Chapter 6 – Computation Tree Logic (pag.e 313-323)

- [2] Ben-Ari, Mordechai, Principles of the Spin Model Checker, ISBN 978-1-84628-770-1, Springer-Verlag London, 2008

- (See Teams Files-Lecture02)

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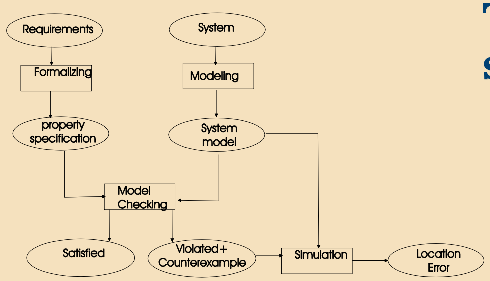
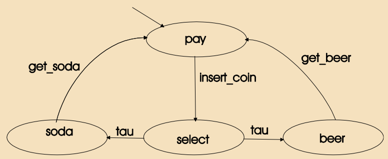
CMES – Today   Bring it All Together

Model checking

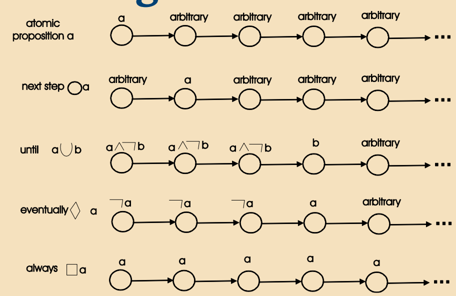


Transition systems

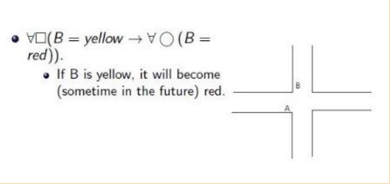


Linear-Time Properties

Linear-Time Logic



Computation Tree Logic



Spin Model Checker

Promela model

Concurrency and Interleaving Semantics

Linear Temporal Logic

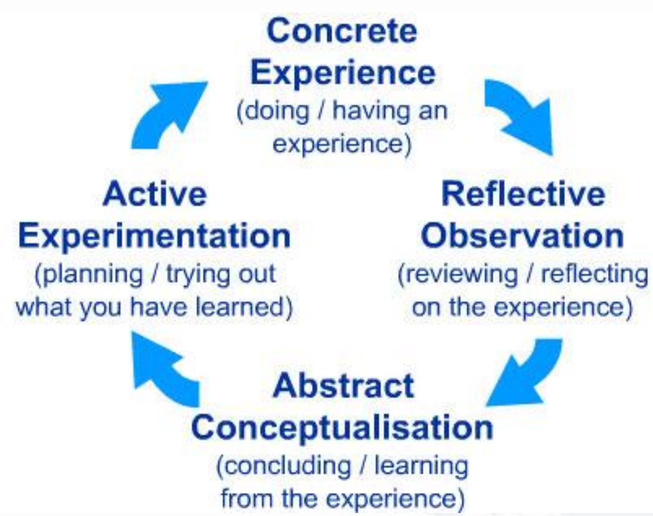
Channels in Promela

Next Lecture

- Prepare before Lecture 3 (Friday, 17 Oct 2025, 18:00-20:00)
  - Read 17 SDG, select 1 SDG, think of a solution
  - Problem definition: 2 actors and 2 signals
  - Install JSpin on your computer (See Teams->Files-> Lecture02)

- 17 SDG (Sustainable Development Goals) and UBBGoesGreen
  - https://sdgs.un.org/goals
  - Read them all and select one
  - Read more about the challenges for that selected SDG
  - Tools
    - https://knowsdgs.jrc.ec.europa.eu/
- UBBGoesGreen
  - http://green.ubbcluj.ro/en/
    - http://green.ubbcluj.ro/wp-content/uploads/Raport-de-dezvoltare-sustenabila_2018.pdf
    - https://green.ubbcluj.ro/wp-content/uploads/Raport-de-dezvoltare-durabila_2021.pdf
  - http://greenmetric.ui.ac.id/
- SDG resources
  - https://sdgresources.relx.com/articles/can-mode-time-and-expense-commuting-work-affect-our-mental-health
- Define a Problem Statement (2 actors and 2 signals)
  - Example: Recycle Paper Solution
    - Actors: Teacher (T), UBB-Recycle-Center (UBB-RC)
    - Signals: T to UBB-RC (haveExamPapersToRecycle) and UBB-RC to T (doYouHaveOtherPapers?);

Having fun learning about Model checking



- Problem definition
- 2 actors – teacher + UBBRecycleCenter
  - T to UBBRC: HaveExamPapersToRecycle?
  - UBBRC to T: DoYouHaveOtherPapers?
- 2 actors – Student + Carrier Adviser
  - Signals – CA→S: What do you like? (AF, C, S)
  - S→CA: How much money? (100, 200)

Concrete Experience

JSpin – Problem implementation

- Form team of X members 5 minutes

(1 needs a computer with JSpin installed)

- Problem definition – 10 minutes
  - 2 Actors
  - 2 “signals” between the actors
- Implement in Promela Language the model 50 minutes
- Write 1 LTL formula 10 minutes

Experience learning

50 XP/student

(All activities: Code + Mentimeter + Form survey)

(20 minutes)

Thank You For Your Attention!

- ExitTicket
- Mentimeter
  - menti.com
  - Code: ?

Software Systems Verification and Validation

"Tell me and I forget, teach me and I may remember, involve me and I learn."

(Benjamin Franklin)