Software Systems Verification and Validation

Lecture 09: Model checking

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Outline

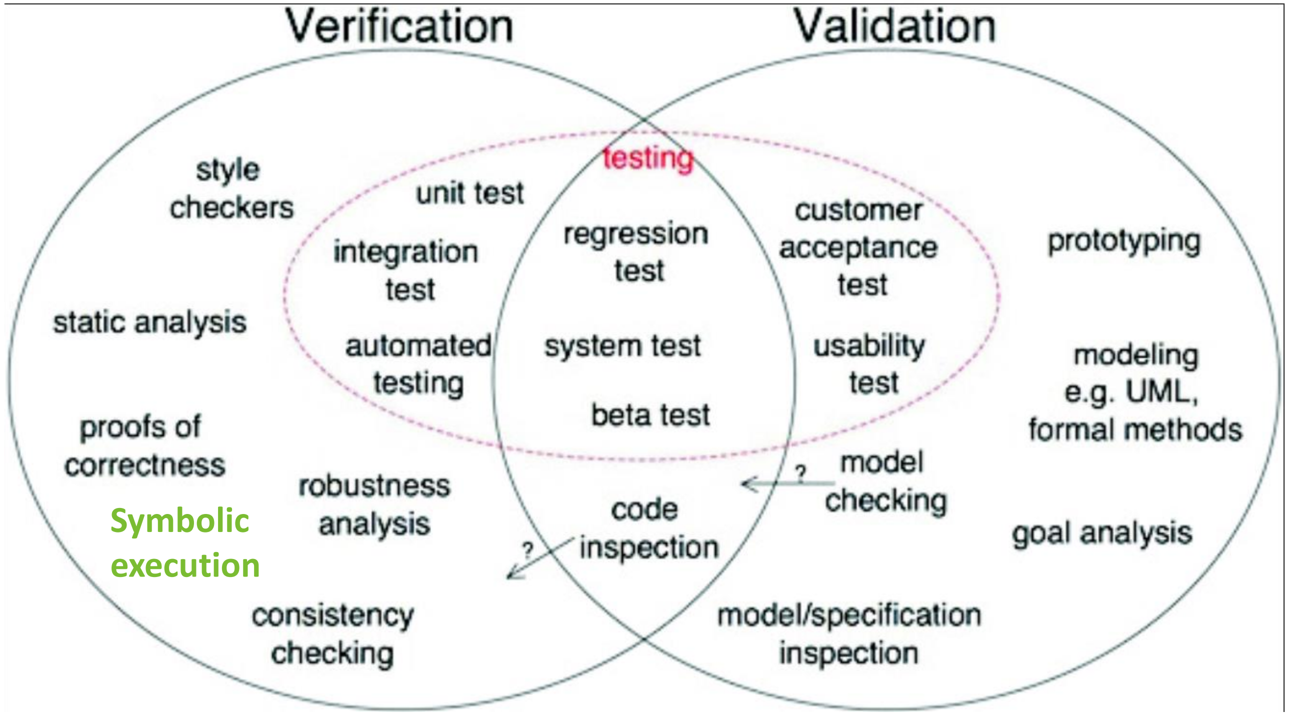
- System verification
- Model checking
- Transition system
- Linear-Time Properties
- Linear-Time Logic
- Computation Tree Logic

- Next lecture:
  - Spin Model Checker (still today!)

- Questions

Sales paradigm - SSVV

- Motivate the STUDENT - what you will learn!

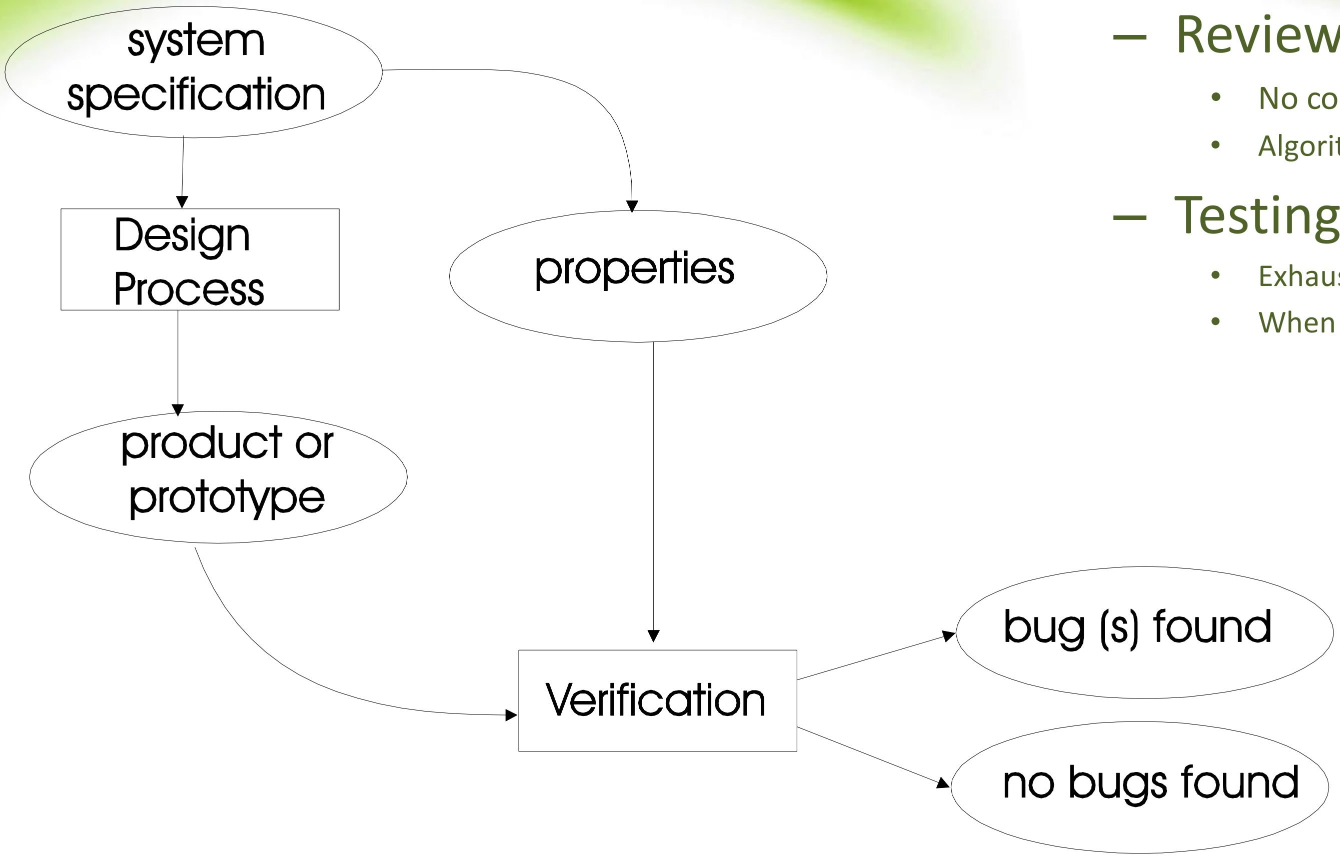


- http://www.easterbrook.ca/steve/2010/11/the-difference-between-verification-and-validation/

System verification (1)

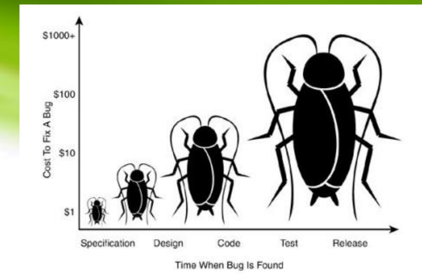
- Information and Communication Technology (ICT)
- Correct ICT systems
  - It is all about money.
  - It is all about safety.
- Reliability of the ICT systems
  - Interactive systems - concurrency & nondeterminism
  - Pressure - to reduce system development time
- System verification techniques

System verification (2)

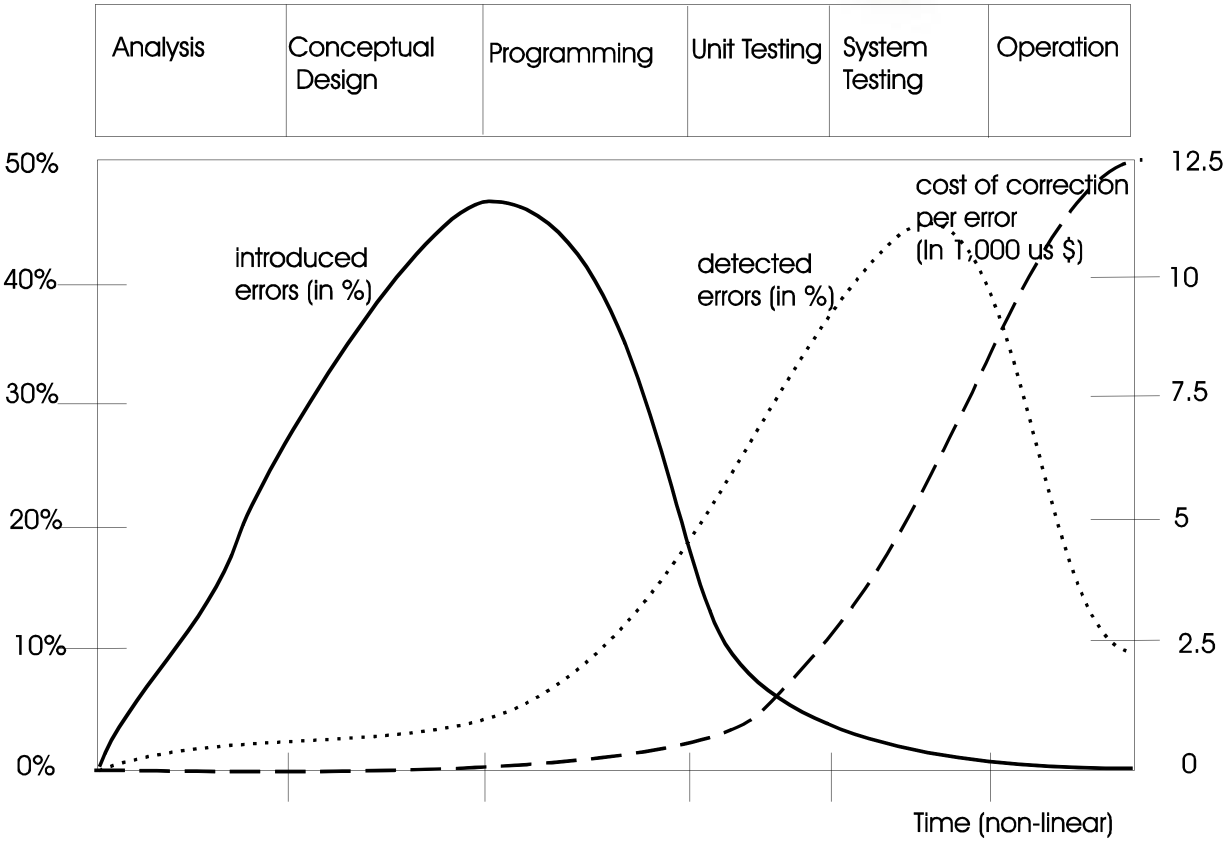


- Software verification
  - Review
    - No concurrency defects
    - Algorithm defects
  - Testing
    - Exhaustive testing?
    - When to stop?

System verification (3)



- Catching software errors: the sooner the better



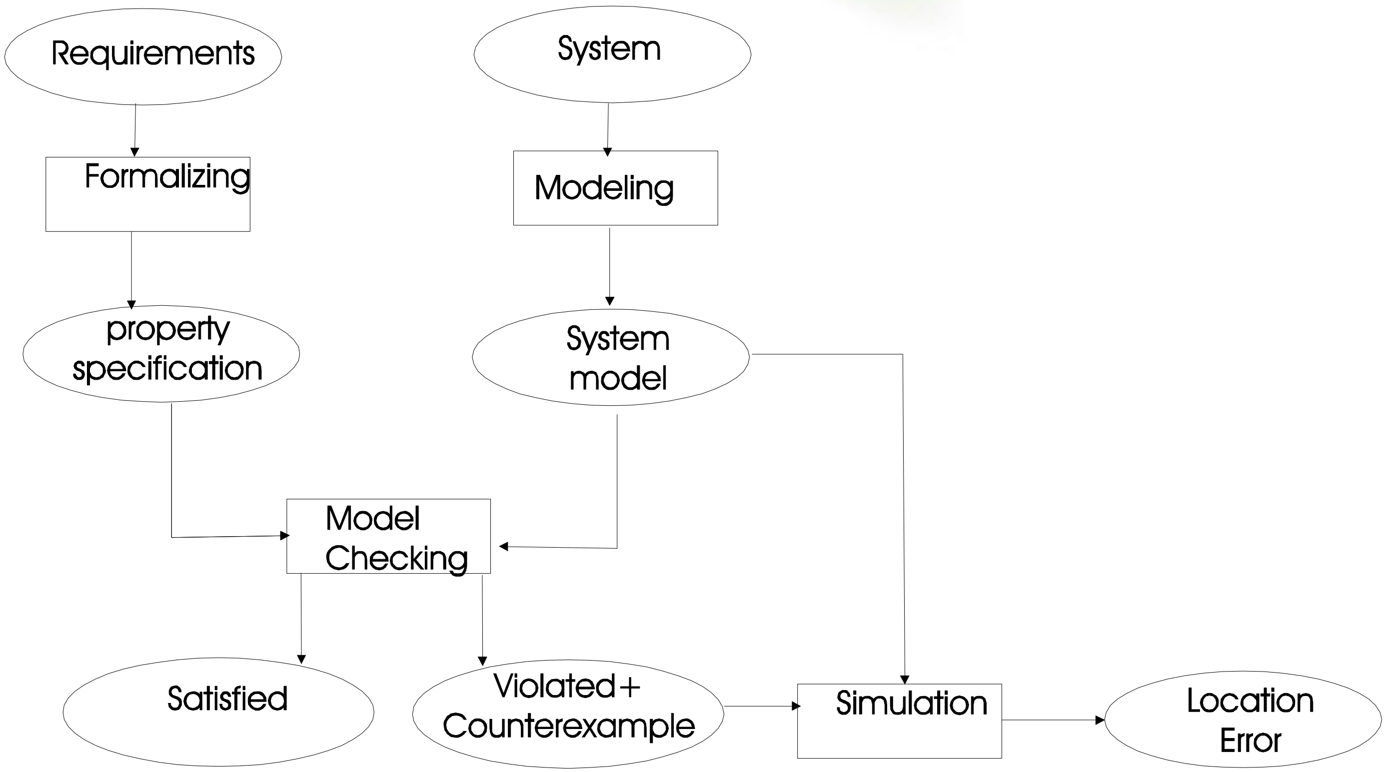
Model checking (1)
Formal methods

- 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 (1)
Formal methods

- 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 some-one yells, “I got it!”

Model checking (2)
Approach



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 and Weaknesses

Strengths

- General verification approach
- Supports partial verification
- Provides diagnostic information
- Potential “push-button” technology
- Increasing interest by industry
- Easily integrated in existing development cycles

Weaknesses

- 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

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,

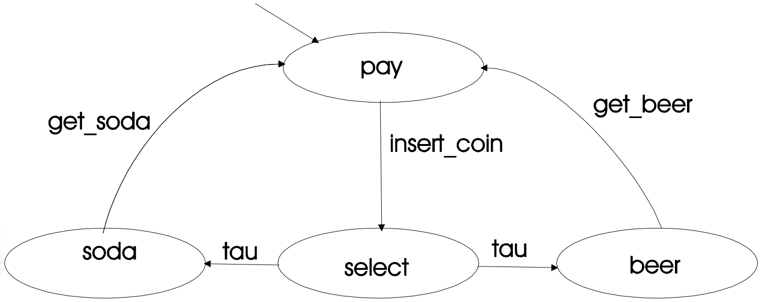
  $s \models \phi$ iff $L(s) \models \phi$.

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."
  $AP = \{paid, drink\}$, $L(pay) = \emptyset$, $L(soda) = L(beer) = \{paid, drink\}$, $L(select) = \{paid\}$.



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) - $\Diamond$
  - "**always**" (now and forever in the future – $\Box$
- 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

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:
  $\varphi ::= true \mid a \mid \varphi_1 \wedge \varphi_2 \mid \neg\varphi \mid \bigcirc \varphi \mid \varphi_1 \bigcup \varphi_2$, where $a \in AP$.

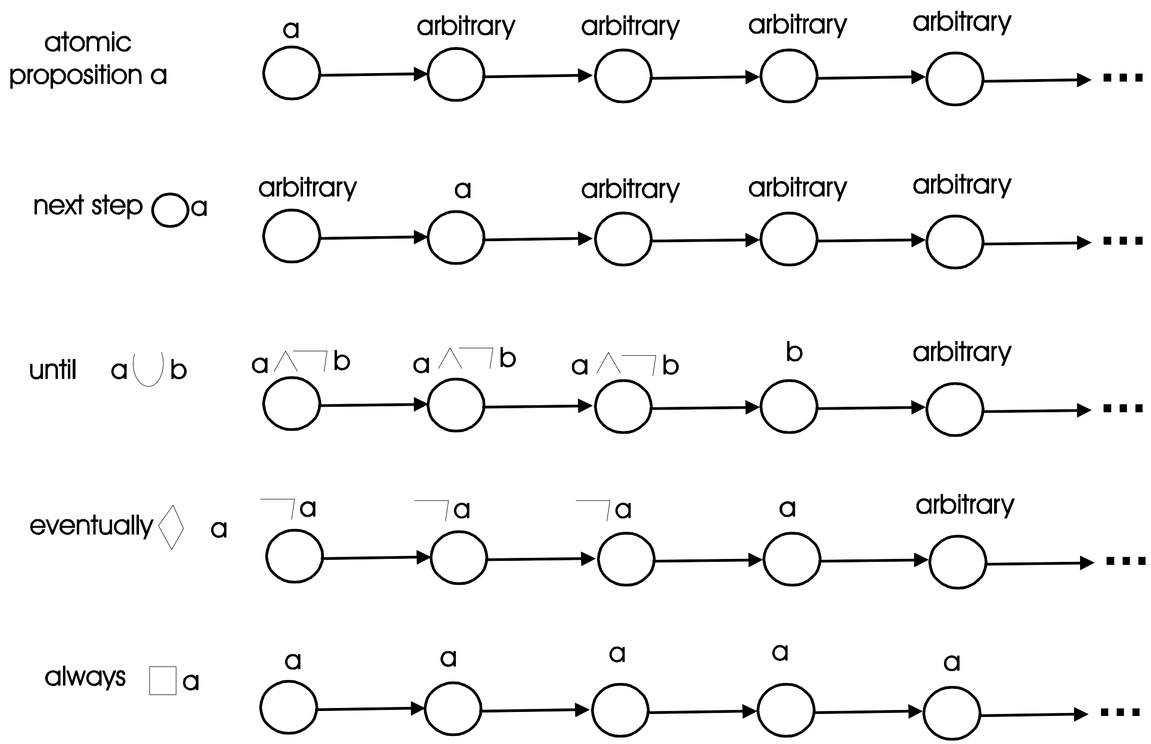
Linear-Time Logic (2)

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:
  - $\Diamond\varphi =$ 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)

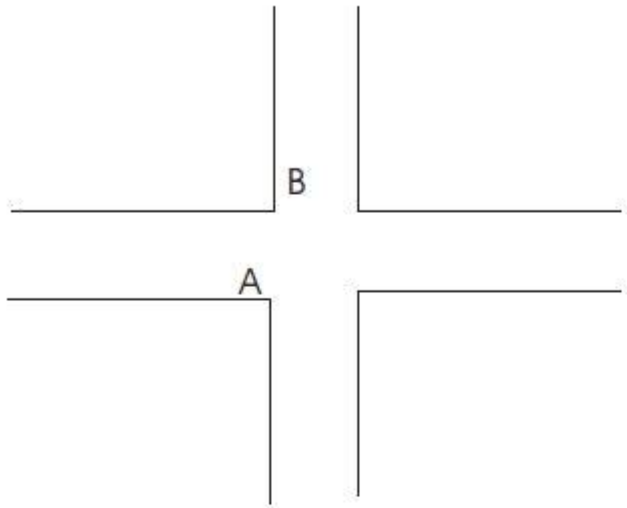
Intuitive meaning of temporal modalities



Linear-Time Logic (4)

LTL semaphore example

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



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

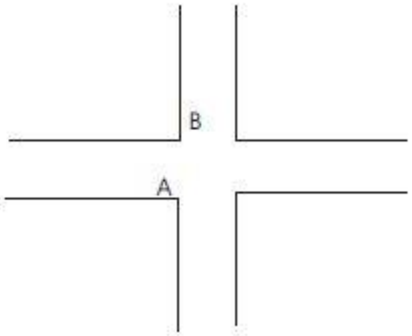
- CTL distinguishes between state formulae and path formulae:
  - State formulae express a property of a state.
  - Path formulae express a property of a path, i.e. an infinite sequence of states.
- Temporal PATH operators $\bigcirc$ and $\bigcup$
  - $\bigcirc\phi$ holds for a path if ϕ holds in the 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 (3)

CTL semaphore example

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



Surprise!

Model checking

3-5 minutes

Formative Assessment

Anonymous voting

Next Lecture (Still today!)

- JSpin

Questions

- Thank You For Your Attention!

References

Sources

[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 (pag. 19-20), Chapter 3 (pag. 89, 107, 120-121), Chapter 5 – Linear Temporal Logic (pag. 229-233), Chapter 6 – Computation Tree Logic (pag. 313-323)