Reasoning about Module Checking

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Short Version

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Model Checking

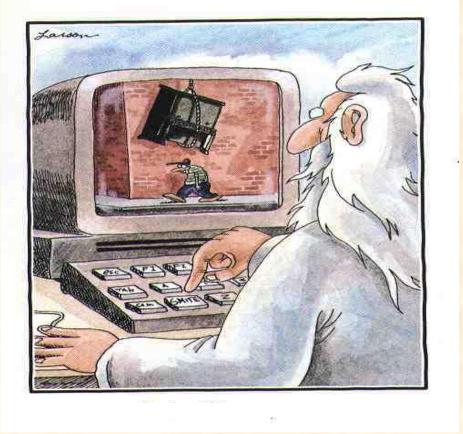
- Let S be a finite-state system and P its desired behavior
  - S → labelled state-transition graph M
  - P → a temporal logic formula ψ
- We check whether S has the required behavior P by checking whether

$$\mathbf{M} \models \psi$$

Classes of Models

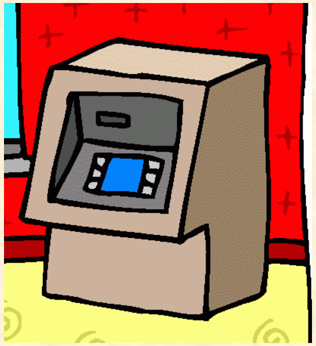
- ❑ Closed Systems
  - ➢ Behavior is fully characterized by system state
- ❑ Open Systems
  - ➢ Behavior depends on the interaction with the environment

It must be "reactive"

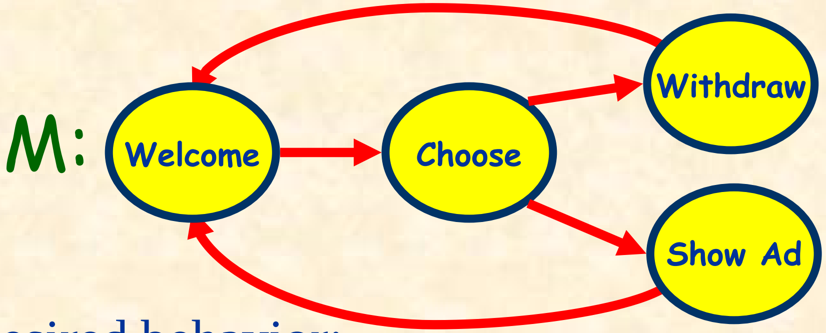


- ➢ Open System Model: ~~Labelled State-Transition Graph~~
- ➢ A solution for Open Finite-State Systems: Module Checking [Kupferman, Vardi, Wolper 1996-2001]

Model checking



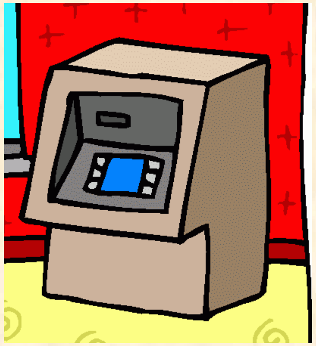
- Consider an ATM machine that
  1. Displays a welcome screen
  2. Makes an internal nondeterministic choice
  3. **Withdraws money** or **shows an advertisement (Ad)**
- The machine is a closed system !
- M is a labeled-state transition graph modeling the machine



- A desired behavior:
  "It is always possible to show an ad"

$\varphi = \forall G \exists F$ **Show Ad**

Model checking



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    1. Displays a welcome screen
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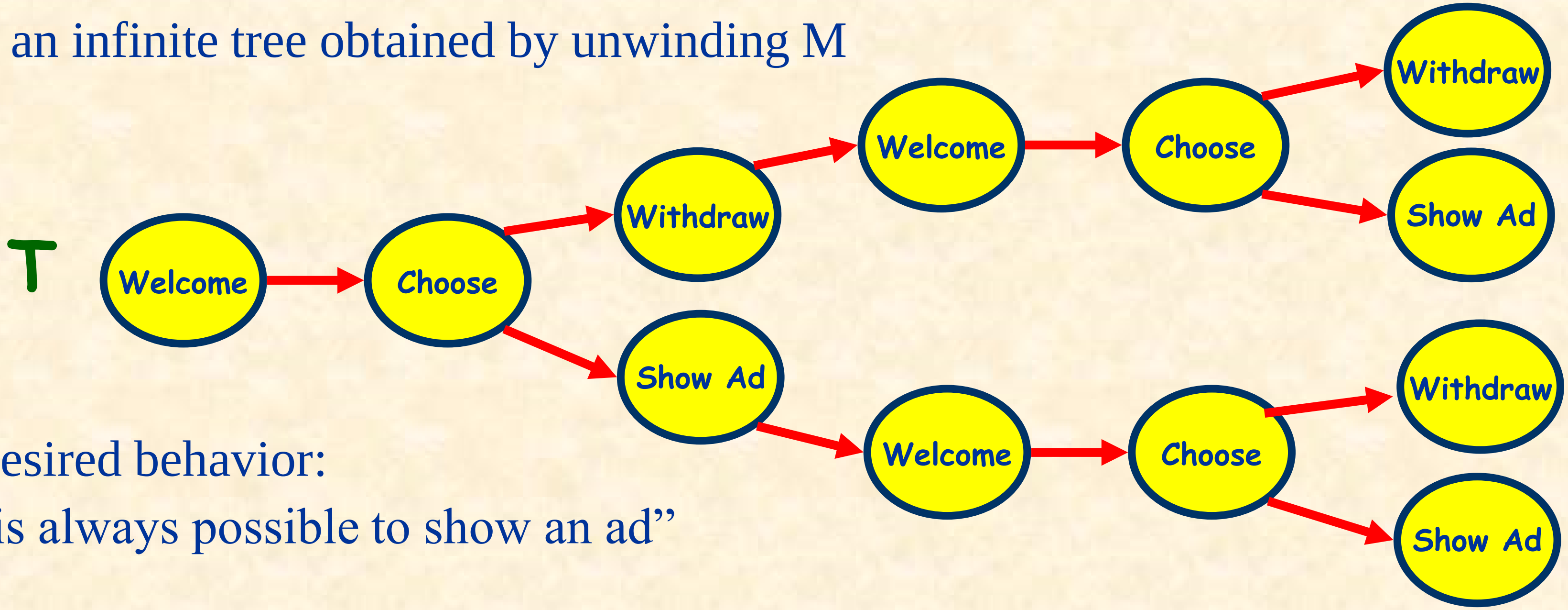
- The machine is a closed system !
- M is a labeled-state transition graph modeling the machine
- T is an infinite tree obtained by unwinding M



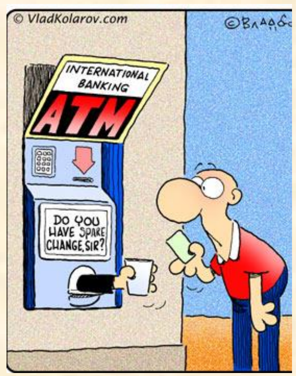
- A desired behavior:
  "It is always possible to show an ad"

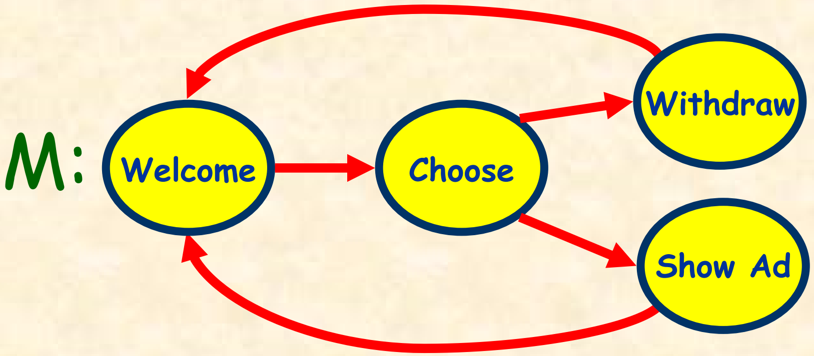
$\varphi = \forall G \exists F$ **Show Ad** ⇒ $M \models \varphi$ **iff** $T \models \varphi$

Model checking an open system

- Consider the ATM machine as an open system:
  1. Displays a welcome screen
  2. Lets the environment choose to view an Ad or withdraw money
  3. Performs the requested operation and restarts from 1

Open system





- The ATM can always eventually show an Ad iff

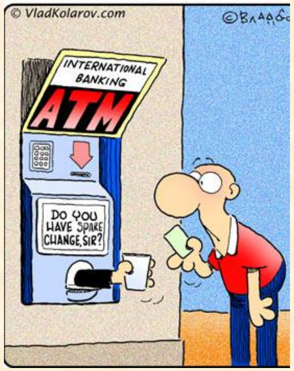
~~$T \models \forall G \, \exists F$ Show Ad~~

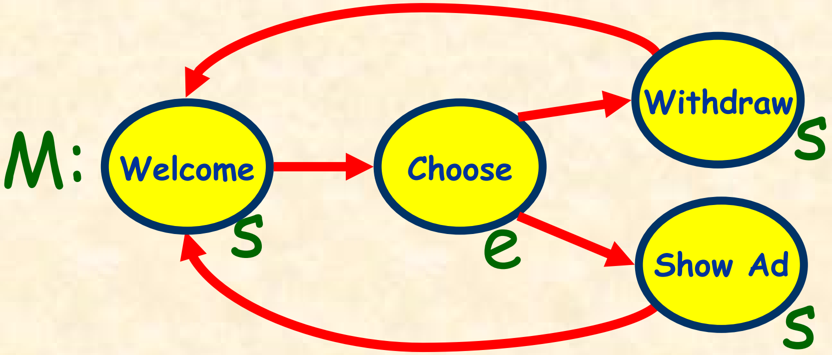
It may be impossible to show an ad!

Model checking an open system

- Consider the ATM machine as an open system:
  1. Displays a welcome screen
  2. Lets the environment choose to view an Ad or withdraw money
  3. Performs the requested operation and restarts from 1

Open system





- To model the ATM we need a **Module**: a labeled transition graph with a partition into system and environment states
- Let T be the unwinding of M.
- Let **Exec(M)** be the set of all trees obtained by pruning in T sub-trees rooted in successors of environment nodes (but one).
- **M (reactively) satisfies φ iff φ holds in all trees of Exec(M).**

Module checking

$M \models_r \varphi$

Solving CTL/CTL* Module Checking

- First, observe that
  - $M \models_r \varphi$ implies $M \models \phi$, while the convers may not be true.
  - $M \not\models_r \varphi$ iff there is a tree T in Exec(M) such that $T \models \neg \varphi$

- An automata-theoretic solution:
  1. Build a tree automaton $A_{Exec(M)}$ that accepts all trees in exec(M)
  2. Build a tree automaton $A_{\neg\varphi}$ that accepts all tree models of $\neg\varphi$
  3. Check whether $M \models_r \varphi$ by checking $L(A_{Exec(M)}) \cap L(A_{\neg\varphi}) = \emptyset$

Finite-state complexity results

Class	Model Checking (formula comp.)	Model Checking (system comp.)	Module Checking (formula complexity)	Module Checking (system complexity)
LTL	PSpace-Complete[4]	NLogSpace [4]	PSpace-Complete [5]	NLogSpace [5]
CTL	Linear Time [1]	NLogSpace[3]	ExpTime-Complete [5]	PTime [5]
CTL*	PSpace-Complete [2]	NLogSpace[3]	2ExpTime-Complete [5]	PTime [5]

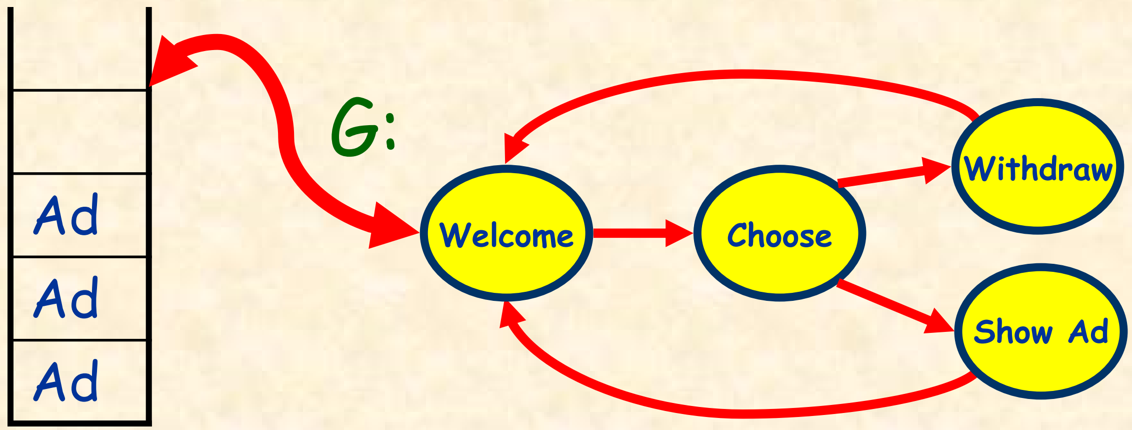
1. [Clarke, Emerson, Sistla 1986]
2. [Emerson and Lei 1985]
3. [Kupferman, Vardi, Wolper 1994 & 2000]
4. [Sistla and Clarke 1985]
5. [Kupferman,Vardi,Wolper 1996 & 2001]

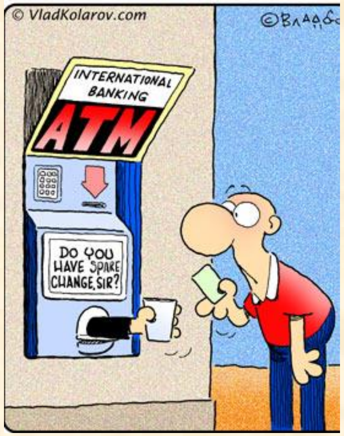
Module Checking Milestones

- Timeline:
  - 1996-2001: CTL/CTL* two-players turn-based finite-state perfect information.
  - 1997: **mu-calculus** two-players **concurrent** finite-state **imperfect** information
  - 2002-2005: Abstraction refinement and implementation.
  - 2005-2010: two-players turn-based **infinite-state** perfect information
  - 2007-2013: two-players **concurrent** infinite-state **imperfect** information
  - And a number of other extensions in the last decade…

Pushdown Module Checking

- Consider an open ATM machine with the constraint
  "it is not possible to make more withdraws than Ads viewed"
- We need a stack to count how many Ads remain to be shown





- A PD is a labeled transition graph augmented with a stack.
- (q,ξ) is a configuration if q is a node of G and ξ is a stack content
- An open PD (OPD) has environment and system configurations
- An OPD induces a Module M where nodes are Pushdown Configurations

PD Module Checking: decide whether $M \models_r \varphi$

- For example: $\mathbf{M \models_r \forall G \exists F}$ **Show Ad** but $\mathbf{M \not\models_r \forall G \exists F}$ **Withdraw**

Pushdown Complexity Results

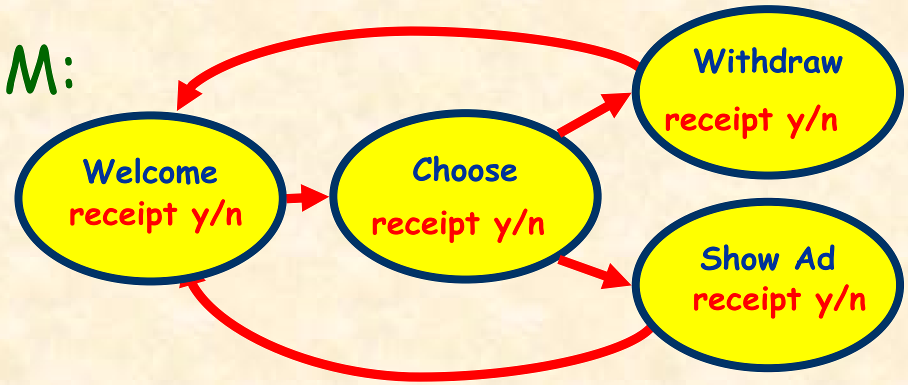
Class	System	PD Model Checking	PD Module Checking
LTL	finite-state	Pspace-Complete	PSpace-Complete
CTL	finite-state	Linear Time [1]	EXPTime-Complete[3]
CTL*	finite-state	PSpace-Complete [2]	2EXPTime-Complete[3]
LTL	Pushdown System	Exptime-Complete	Exptime-Complete
CTL	Pushdown System	EXPTime-Complete[4]	**2EXPTime-Complete[5]**
CTL*	Pushdown System	2EXPTIME-Complete[4]	**3EXPTime-Complete[5]**

1. [Clarke, Emerson, Sistla 1986]
2. [Emerson and Lei 1985]
3. [Kupferman, Vardi, Wolper 2001]
4. [Walukiewicz 2000]
5. [Bozzelli, Murano, Peron, 2005-2010]

Exptime-Complete w.r.t the system (fixed formula)

(PD) Module Checking with Imperfect Information

- The environment can have imperfect information (hidden information) regarding the (control) state and the stack content.



- The environment does not see the full picture!
  …but must act independently of the missing information…
- Not all the trees in EXEC(M) correspond to an actual environment .
- M reactively satisfies φ iff φ holds in all **consistent** (uniform) trees of Exec(M).
- Checking this consistency is the main difficulty here.
- [Aminof, Murano, Vardi] Using alternating state PD tree automata, we have proved decidability if the imperfect information resides only in the control states.

From Two Players to Multi Players

- In 1997, module checking "took" also another direction to deal with multi-player concurrent games

Alternating-Time Temporal Logic

Alternating-Time Temporal Logic

- ATL generalizes CTL: temporal operators are indexed by coalitions of agents.

$$\varphi := true \mid p \mid \varphi \wedge \varphi \mid \neg\varphi \mid \langle\langle A \rangle\rangle \psi \qquad \psi := X\, \varphi \mid \varphi\, U\, \varphi \mid \varphi\, R\, \varphi$$

- $\langle\langle A \rangle\rangle\ \psi$ means that the team of agents A has a (collective) strategy to enforce ψ.

- ATL formulas are generally interpreted over Concurrent Game Structures (CGS): a Kripke structure whose transitions are labeled with agents' decisions.
- ATL is a story of success with several applications in MAS!

A (refuted) common belief

- Since its definition, there has been a common belief:

  ATL$^{(*)}$ model checking subsumes CTL$^{(*)}$ module checking!!!

- In Murano and Jamroga AAMAS 2014 it has been showed that it is not the case!
  - In module checking environment's strategies are nondeterministic and irrevocable.
  - In ATL$^{(*)}$ agents can only use deterministic and revocable strategies.
  - ATL$^{(*)}$ model checking does not have the distinguishing and expressive power of CTL$^{(*)}$ module checking
  - To subsume CTL(*) module checking we have introduced the logic MNIATL(*)

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ATL module checking

- In Murano and Jamroga - AAMAS 2015, finally a new framework that combines and extends the features of the two methodologies has been introduced:
  - The environment is a special agent acting as in classic module checking: it has nondeterministic irrevocable strategies, possibly acting under imperfect information
  - The other agents act as in classic ATL.

Conclusion

- Model checking has been conceived in the 1980s to check **closed systems**
  - Model behavior determined by internal states.
  - One source of nondeterminism: the unwinding returns an infinite computation tree
  - Model checking amounts checking whether this **unique tree** satisfies the specification
- Module checking is a powerful method proposed in 1990s for **open systems:**
  - Open systems adapt their behavior to the input received from the environment
  - Two sources of nondeterminism: an additional external one from the environment
  - All possible interactions system-environment induce an infinite set of trees (Exec(M))
  - Module checking amounts checking whether **all these trees** satisfy the specification
- In the last 20 years, Module checking has been investigated in several settings:
  - Turn-based/concurrent, perfect/imperfect information, finite/infinite state, etc. ☺
- Little work has been done on the connection with other methodologies in open system verification and little investigation of its application in AI! ☺ ☺

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