# Model Checking of Software

Patrice Godefroid

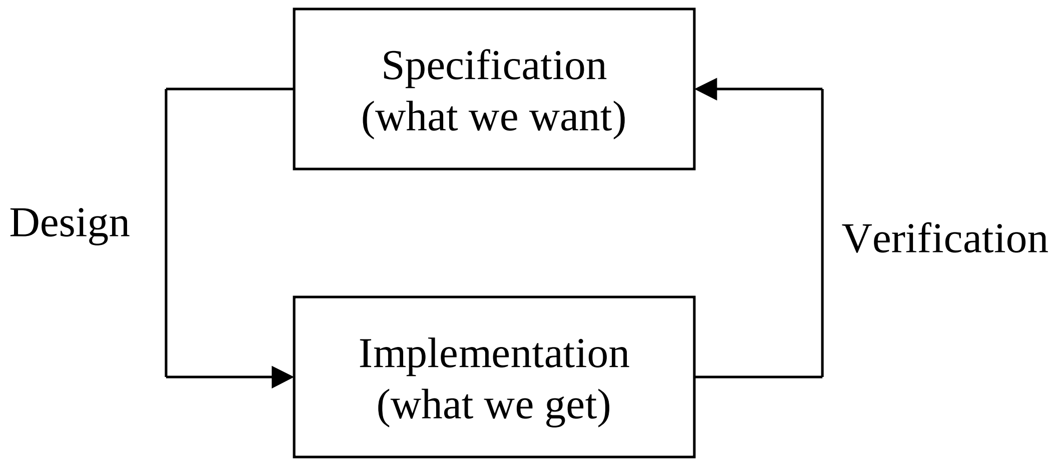
Bell Laboratories, Lucent Technologies

# A Brief History of Model Checking

- Prehistory: transformational programs and theorem proving
- Early 80’s: foundations (the pioneers)
- Late 80’s: first tools… (the first champions)
- Early 90’s: reality check: state spaces explode! (the engineers)
- Late 90’s: the boom… then reality check… (the entrepreneurs)
- Next: can model checking be applied to software?
  - Challenges and approaches currently being investigated…

# Preliminaries: Formal Verification + Disclaimer

- What is Verification? 4 elements define a verification framework:




**Verification**: to check if **all** possible behaviors of the implementation are compatible with the specification

- While testing can only find errors, verification can also prove their absence (=exhaustive testing).

- Disclaimer: emphasis on technical ideas, not references…

# Prehistory (70’s and before)

- “Transformational” programs:
  - Most early computer programs were designed to **compute** something.
  - Examples: accounting, scientific computing, etc.
  - Transformation from initial to final state.
  - Specification= pre-condition/post-condition
- Formal verification:
  - Paper and pencil.
  - Using **Theorem Proving** (first CAV tools)

# Theorem Proving

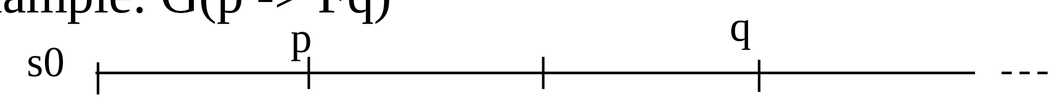
- Goal: automate mathematical (logical) reasoning.
- Verification using theorem proving:
  - Implementation represented by a logic formula I (ex: Hoare's logic).
  - Specification represented by a logic formula S.
  - Does "I implies S" hold?
  - Proof is carried out at syntactic level.
- This approach is very general.
  - Many programs and properties can be checked this way.
- However, most proofs are not fully automatic.
  - A theorem prover is rather a proof assistant and a proof checker.

# Early 80's: Foundations (the pioneers)

- From transformational programs to **reactive programs**:
  - A transformational program **computes** something.
  - A reactive program **controls** something.
  - Examples: telephone switch, airplane, ATM, power plant, pacemaker, etc.
- A reactive program continually interacts with its environment.
- Viewed as a FSM (automaton), called the **state space**.
- Behavior described in terms of sequences of states/transitions.
- Language for temporal properties: **Temporal Logic** [Pnueli,…]

# Temporal Logic Model Checking

- Example: Linear-time Temporal Logic (LTL)
  - Specify properties of infinite sequences of states (or transitions).
  - Temporal operators include: G (always), F (eventually) and X (next).
  - Example: G(p -> Fq)




- "Does M satisfy f ?" = **model checking** [Clarke, Emerson, Sifakis,…]
  - For f in LTL, do all infinite computations of M satisfy f?
  - For f in BTL, does the computation tree of M satisfy f?

- Algorithmic issues: efficient decision procedures exist…
  - Proof can be carried out at semantic level, via state-space exploration.
  - Ex: for CTL, SAT is EXPTIME-complete, but model checking is linear!

# First Model-Checking Frameworks

- 4 components define a model-checking framework:
  - Implementation (program) = an FSM.
  - Specification (property) = a temporal logic formula.
  - Comparison Criteria = defined by semantics of the temporal logic.
  - Algorithm = evaluates the formula against the FSM (“model-checking algorithm”)
- Model-Checking Research in the 80’s:
  - Various temporal logics: linear-time, branching-time,…
  - Relationship between temporal logics and classes of automata (LTL and word automata; BTL and tree automata…)
  - Classes of temporal properties (safety, liveness,…)
  - Etc.
- Model checking is automatic but (essentially) restricted to finite-state systems.
- Many reactive systems can be modeled by FSMs! Let’s build tools!

# Late 80's: First tools… (the first champions)

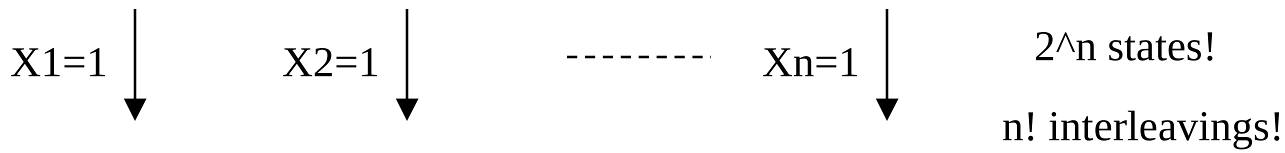
- Examples: CAESAR, COSPAN, CWB, MURPHI, SPIN, etc.
  - Differ by specification language, implementation language, comparison criterion, and/or verification algorithms,
  - but all based on systematic state-space exploration.
- NOTE: using a temporal logic is not mandatory.
  - Many "model-checking" tools do not support a full temporal logic.
  - From now on, no distinction here between model checking and systematic state-space exploration.
  - Logic is a powerful theoretical tool (characterizes classes of properties).
  - Logic can be very useful in practice too (concise and expressive).
- First **success stories** in analyzing circuit designs, communication protocols, distributed algorithms!

# Formal Verification vs. Testing

- Experiments with these tools show that model checking can be very useful!
  - Main strength: model checking can detect subtle design errors.
- In practice, formal verification is actually **testing** because of approximations:
  - when modeling the system,
  - when modeling the environment,
  - when specifying properties,
  - when performing the verification.
- Therefore “bug hunting” is really the name of the game!
  - Main goal: find errors that would be hard to find otherwise.

# Early 90s: First Reality Check… (the engineers)

- Model Checking is limited by the **state explosion problem**.




  - FSM (=state space) can itself be the product of smaller FSMs…
  - Model checking is usually linear in the size of the state space,
  - but the size of the state space is usually exponential (or worse) in the system description (program).

- State-space exploration is fundamentally hard (NP, PSPACE or worse).

- Engineering challenge: how to make model checking scalable?

# Dealing with State Explosion

- Divide-and-conquer approaches:
  - abstraction: hide/approximate details.
  - compositionality: check first local properties of individual components, then combine these to prove correctness of the whole system.
- Algorithmic approaches:
  - "symbolic verification": represent state space differently (BDDs,…).
  - state-space pruning techniques: avoid exploring parts of the state space (partial-order methods, symmetry methods,…).
  - Techniques to tackle the effects of state explosion (bit-state hashing, state-space compression, caching, etc.).
  - Etc.
- Several order of magnitudes gained! We are in business!

# Late 90's: the boom… then reality check…

- "Industrial" model-checking tools are developed and gain acceptance in industry…
  - Become routinely used for some applications in some companies.
- Mostly hardware: IBM, Intel, Lucent, Motorola, etc.
- Software designs too (with SDL (Telelogic), VFSM (Lucent),…)
- Several start-ups are trying to emerge!…
  - FormalCheck (now Cadence), Verisity, Verysys, Mentor Graphics, 0-in,…
- Making money selling model-checking tools is hard!
  - Scalability issues (state explosion…)
  - Usability issues (requires training for specification and verification)

# Applications: Hardware

- **Hardware verification** is an important application of model checking and related techniques.
  - The finite-state assumption is not unrealistic for hardware.
  - The cost of errors can be enormous (e.g., Pentium bug).
  - The complexity of designs is increasing very rapidly (system on a chip).
- However, model checking still does not scale very well.
  - Many designs and implementations are too big and complex.
  - Hardware description languages (Verilog, VHDL,…) are very expressive.
  - Using model checking properly requires experienced staff.
- Quid for Software?

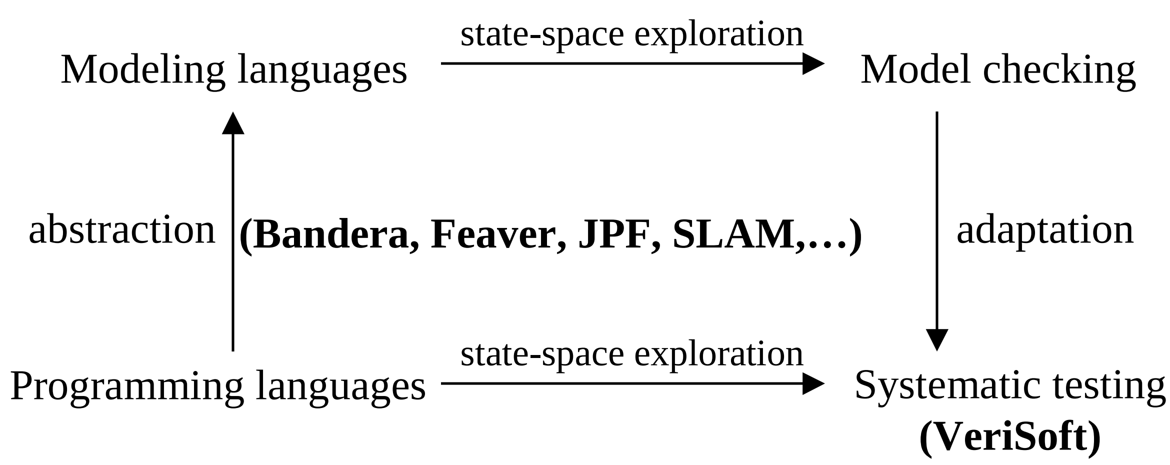
# Applications: Software Models

- Analysis of software models: (e.g., SPIN)
  - Analysis of communication protocols, distributed algorithms.
  - Models specified in extended FSM notation.
  - Restricted to design.
- Analysis of software models that can be compiled: (e.g., SDL, VFSM)
  - Same as above except that FSM can be compiled to generate the core of the implementation.
  - More popular with software developers since reuse of “model” is possible.
  - Analysis still restricted to “FSM part” of the implementation.

# Model Checking of Software

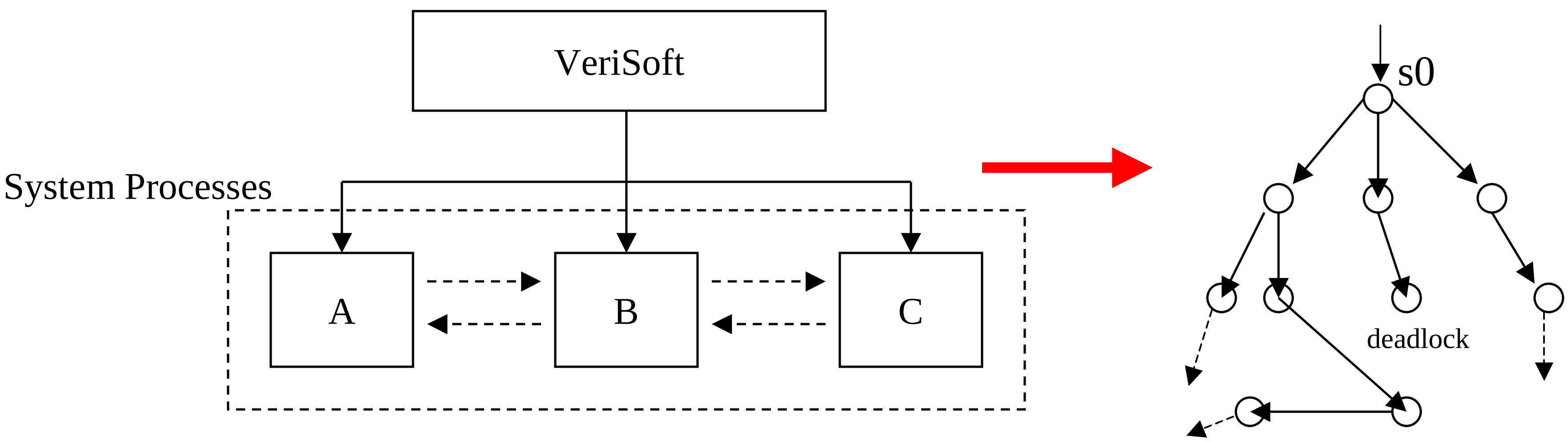
- Challenge: how to apply model checking to analyze **software**?
  - "Real" programming languages (e.g., C, C++, Java),
  - "Real" size (e.g., 100,000's lines of code).

- Two main approaches for software model checking:



# Approach: Systematic Testing (VeriSoft)

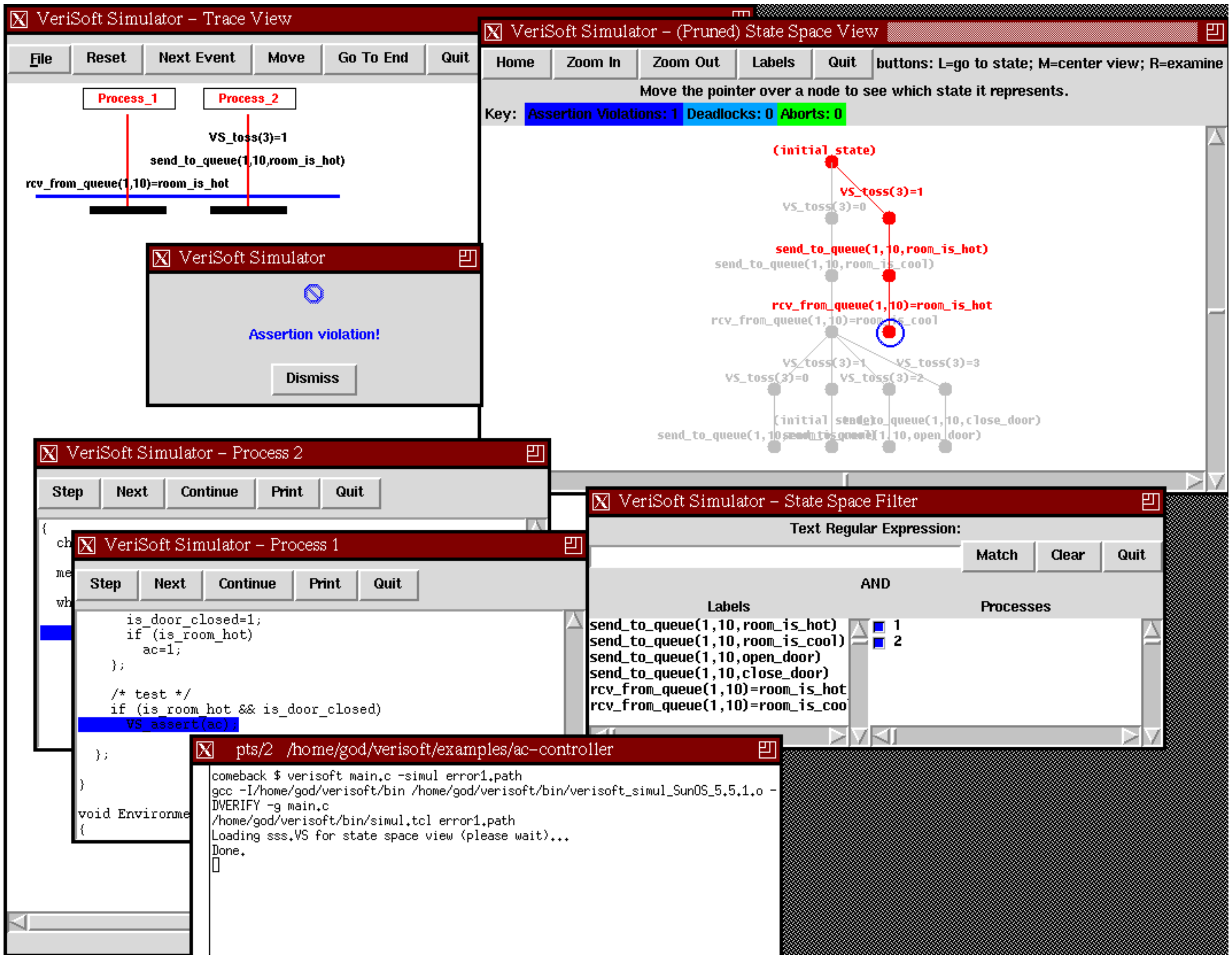
- Control and observe the execution of concurrent processes of the system under test by intercepting system calls (communication, “VS_toss(n)”, assertion violations, etc.).
- Systematically drive the system along all the paths (=scenarios) in its state space (=automatically generate, execute and evaluate many scenarios).
- From a given initial state, one can always guarantee a complete coverage of the state space up to some depth.



# VeriSoft State-Space Search

- Automatically searches for: (safety properties only!)
  - deadlocks,
  - assertion violations,
  - divergences (a process does not communicate with the rest of the system during more than x seconds),
  - livelocks (a process is blocked during x successive transitions).
- A scenario (path) is reported for each error found.
- How to efficiently explore state spaces without storing any state?
  - States of arbitrary (OS) processes are too complex to be represented explicitly (no hash-tables, BDDs,…).
  - For concurrent systems, need partial-order algorithms! [Godefroid,…]

# The VeriSoft Simulator



# VeriSoft Project Status

- Development of research prototype started in 1996.
- Examples of applications in Lucent Technologies:
  - 4ESS Heart-Beat Monitor debugging and unit testing (Switching, switch maint.)
  - WaveStar 40G R4 integration and system testing (Optical, network management)
  - CDMA Call Processing Library testing (Wireless, call processing)
- VeriSoft 2.0 available outside Lucent since January 1999:
  - 100's of non-commercial licenses in 25+ countries; 10's of commercial licenses; several industrial users (Lucent, Cisco, Motorola, Philips,…)
- Examples of related research issues:
  - How to automatically close open reactive programs? [Colby, Godefroid, Jagadeesan,..]
  - How to analyze effectively partial state-spaces? [Bruns, Godefroid,…]
  - How to apply and optimize this approach to multi-threaded programs? [Stoller,…]

# Approach: Automatic Abstraction

- Main ideas and issues:
  - 1. Abstract: extract a model out of concrete program via static analysis.
    - Which programming languages are supported? ((subset of) C, Java, Ada,DSL?)
    - Additional assumptions? (Pointers? Recursion? Concurrency?…)
    - What is the target modeling language? ((C)(E)FSMs, PDAs,…)
    - Can/must the abstraction be guided by the user? How?
  - 2. Model check the abstraction.
    - What properties can be checked? (Safety? Liveness?,…)
    - How to model the environment? (Closed or open system ?…)
    - Which model-checking algorithm? (New algorithms for PDAs, HSMs,…)
    - Is the abstraction “conservative”?
  - 3. Map abstract counter-examples back to code.
    - Behaviors violating the property may have been introduced during Step 1.
    - Hence, need to map scenarios leading to errors back to the code. HOW?

# Active Area of Research…

- Examples of tools:
  - Bandera [Dwyer, Hatcliff,…]: Java to SPIN/SMV/* using user-guided abstraction mapping and slicing/abstract-interpretation/*
  - SLAM [Ball, Rajamani,…]: C to "Boolean programs" (=CFG+boolean variables); automatic abstraction refinement using predicate abstraction…
  - JavaPathFinder [Havelund,Penix,Visser,…]: Java model-checking using special JVM and model-checker…
  - Feaver [Holzmann,…]: C to SPIN using user-specified abstraction mapping…
  - Etc! (Tools for Ada, static analysis of concurrent programs,…)
- Examples of frameworks: (automatic abstraction refinement)
  - [Graf,Saidi,…], [Clarke,Grumberg,Jha,…], [Ball,Rajamani,Podelski,…], [Dill,Das,…], [Khurshan,Namjoshi,…], [Dwyer,Pasareanu,Visser,…], [Bruns,Godefroid,Huth,Jagadeesan,Schmidt…], [Henzinger,…], etc.

# Summary: Two (Complementary) Approaches

- Systematic software testing:
  - Idea: control the execution of concurrent processes by intercepting systems calls related to communication, and automatically drive the entire system through many scenarios.
  - Flexible and scalable approach (code independent).
  - Counterexamples arise from code execution (sound).
  - Provide complete state-space coverage up to some depth only (incomplete).
- Static analysis for automatic model extraction:
  - Idea: parse code to generate an abstract model which is then analyzed by model-checker; abstraction may/must be guided by the user.
  - Coverage can be exhaustive (can be complete).
  - Abstraction may cause spurious counterexamples (unsound)…
  - Technology less mature, active area of research.

# Conclusions

- Model Checking is a very successful research area:
  - New: original approach to check the correctness of reactive systems.
  - Non-obvious: rich theory behind it.
  - Useful: many applications and success stories, including in industry.
- From a business perspective, the success is mixed…(!?!)
- Can model checking be applied to software?
  - Hard problem (model checking + program analysis).
  - Good for research!
  - Bad for business?