Lecture 1:
Model Checking

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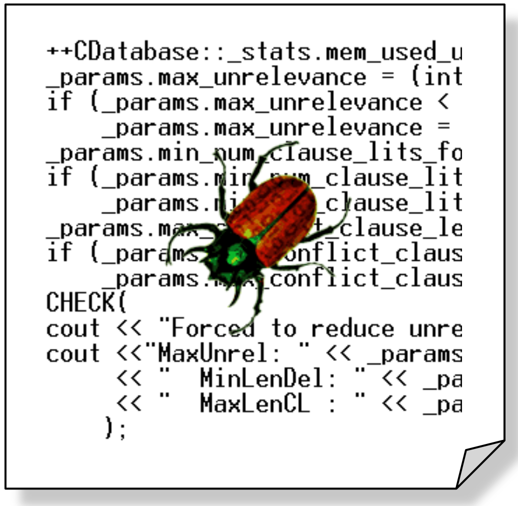


June 2002

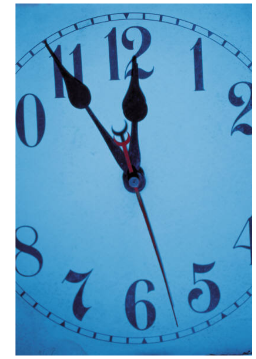
"Software bugs, or errors, are so prevalent and so detrimental that they cost the U.S. economy an estimated $59.5 billion annually, or about 0.6 percent of the gross domestic product

…

At the national level, over half of the costs are borne by software users and the remainder by software developers/vendors."

NIST Planning Report 02-3
The Economic Impacts of Inadequate Infrastructure for Software Testing

"The study also found that, although all errors cannot be removed, more than a third of these costs, or an estimated $22.2 billion, could be eliminated by an improved testing infrastructure that enables earlier and more effective identification and removal of software defects."



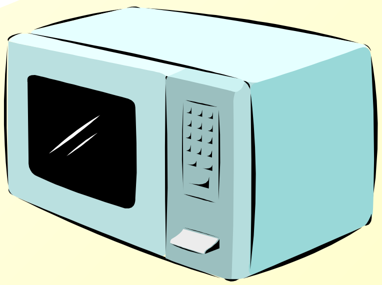
Model Checking

- Developed independently by **Clarke and Emerson** and by **Queille and Sifakis** in early 1980's.
- **Properties** are written in **propositional temporal logic.**
- Systems are modeled by **finite state machines**.
- Verification procedure is an **exhaustive search of the state space** of the design.
- Model checking **complements** testing/simulation.

Advantages of Model Checking

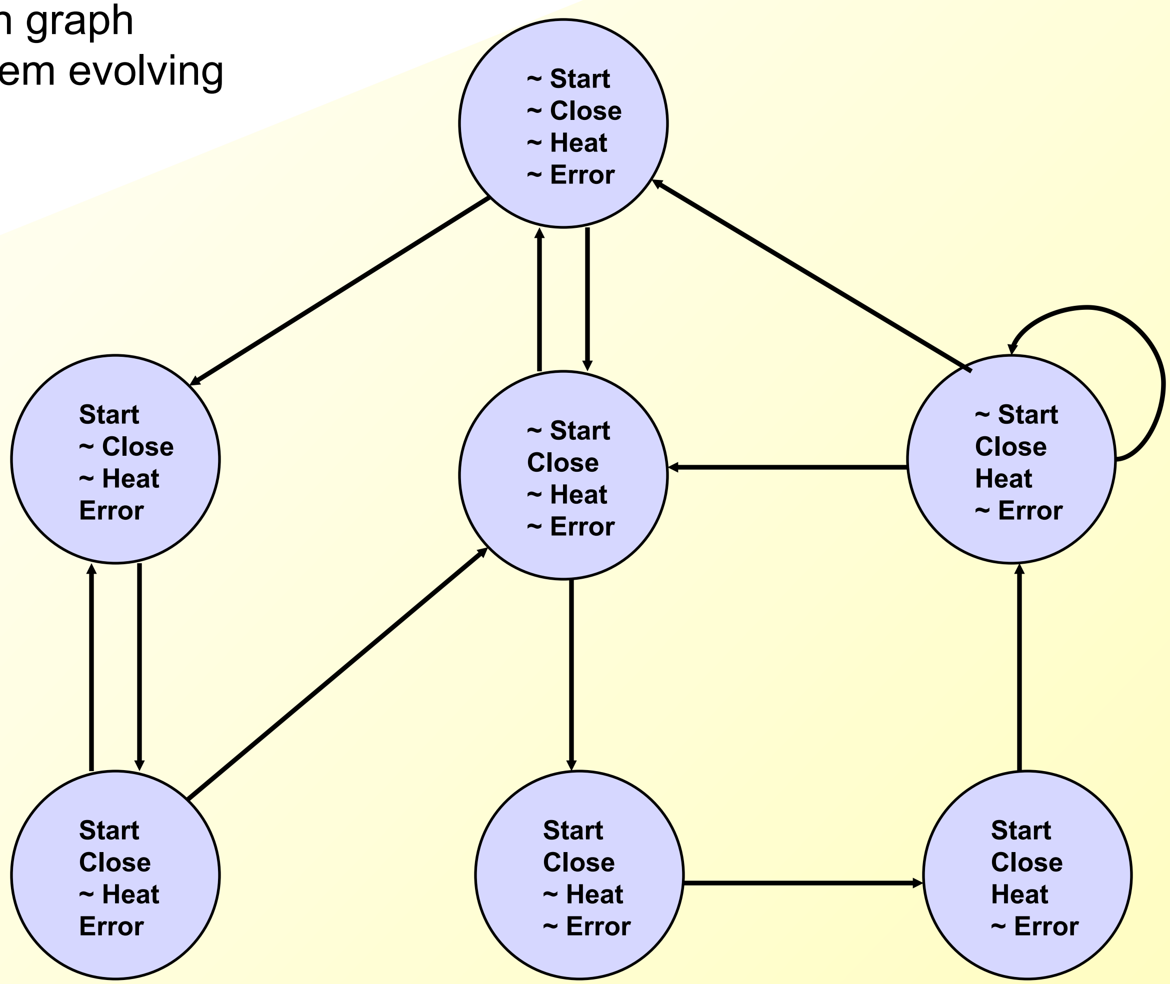
- **No proofs!!!**
- **Fast (compared to other rigorous methods)**
- **Diagnostic counterexamples**
- **No problem with partial specifications / properties**
- **Logics can easily express many concurrency properties**

Model of computation



Microwave Oven Example

State-transition graph describes system evolving over time.



Temporal Logic

- The oven doesn't **heat up** until the **door is closed**.
- **Not heat_up** holds **until door_closed**
- **(~ heat_up) U door_closed**

Basic Temporal Operators

The symbol "**p**" is an atomic proposition, e.g. "**heat_up**" **or** "**door_closed**".

- **F**p - p holds sometime in the ***future.***
- **G**p - p holds ***globally*** in the future.
- **X**p - p holds ***next*** time.
- p**U**q - p holds ***until*** q holds.

Model Checking Problem

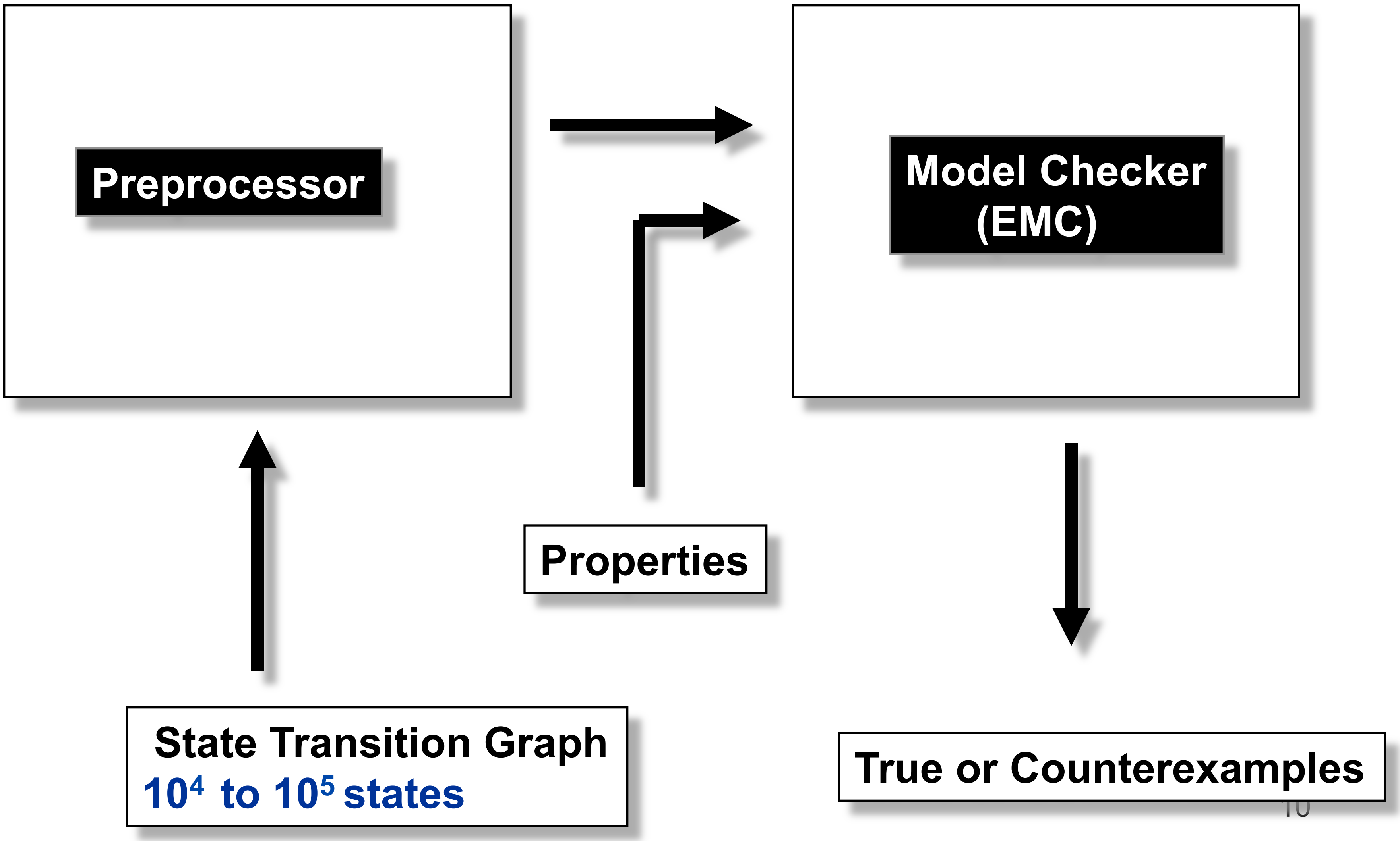
Let ***M*** be a model, i.e., a **state-transition graph**.

Let ***f*** be the **property** in temporal logic.

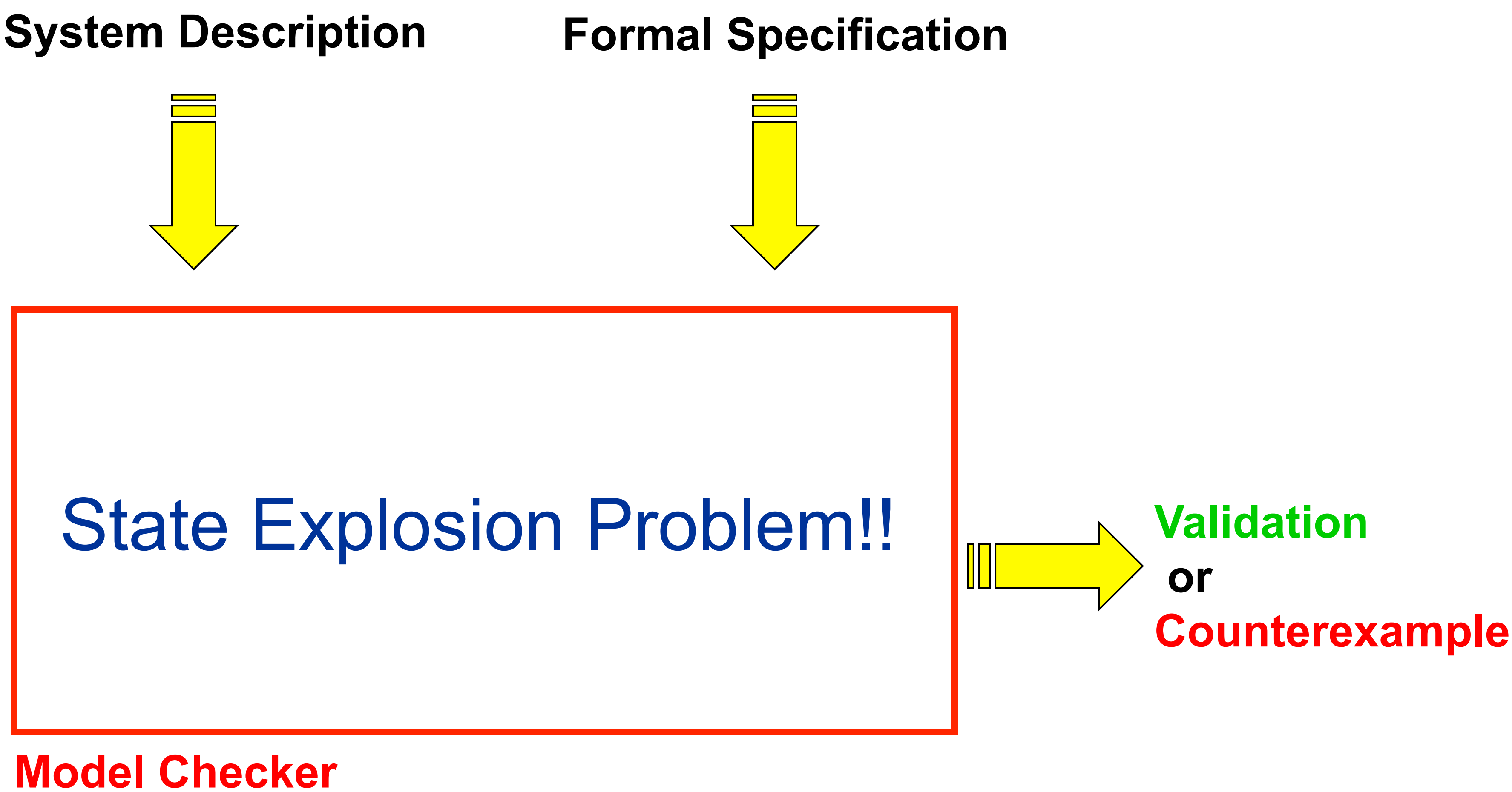
Find all states ***s*** such that ***M*** has property ***f*** at state ***s***.

Efficient Algorithms: CE81, CES83

The EMC System 1982/83

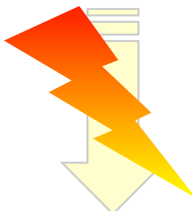


Model Checker Architecture



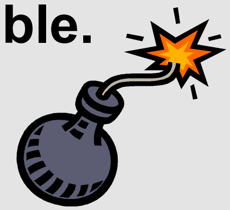
The State Explosion Problem

System Description



State Transition Graph

Combinatorial explosion of system states renders explicit model construction infeasible.



Exponential Growth of …

… global state space in number of concurrent components.

… memory states in memory size.

Feasibility of model checking inherently tied to handling state explosion.

Combating State Explosion

- **Binary Decision Diagrams** can be used to represent state transition systems more efficiently.
  → **Symbolic Model Checking 1992**

- **Semantic techniques** for alleviating state explosion:
  – Partial Order Reduction.
  – Abstraction.
  – Compositional reasoning.
  – Symmetry.
  – Cone of influence reduction.
  – Semantic minimization.

Model Checking since 1981

1981 Clarke / Emerson: CTL Model Checking
Sifakis / Quielle
1982 EMC: Explicit Model Checker
Clarke, Emerson, Sistla

10^5

1990 Symbolic Model Checking
Burch, Clarke, Dill, McMillan
1992 SMV: Symbolic Model Verifier
McMillan

10^{100}

1990s: Formal Hardware Verification in Industry: Intel, IBM, Motorola, etc.

1998 Bounded Model Checking using SAT
Biere, Clarke, Zhu
2000 Counterexample-guided Abstraction Refinement
Clarke, Grumberg, Jha, Lu, Veith

10^{1000}

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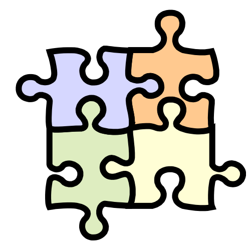


1998 Bounded Model Checking using SAT
Biere, Clarke, Zhu → **CBMC**

2000 Counterexample-guided Abstraction Refinement
Clarke, Grumberg, Jha, Lu, Veith → **MAGIC**

Grand Challenge:
Model Check Software !

What makes Software Model Checking different ?

What Makes Software Model Checking Different ?

- Large/unbounded base types: **`int`**, **`float`**, **`string`**
- User-defined types/classes
- Pointers/aliasing + unbounded #'s of heap-allocated cells
- Procedure calls/recursion/calls through pointers/ dynamic method lookup/overloading
- Concurrency + unbounded #'s of threads

What Makes Software Model Checking Different ?

- Templates/generics/include files
- Interrupts/exceptions/callbacks
- Use of secondary storage: files, databases
- Absent source code for: libraries, system calls, mobile code
- Esoteric features: continuations, self-modifying code
- Size (e.g., MS Word = 1.4 MLOC)

Grand Challenge: **Model Check Software !**

Early attempts in the 1980s failed to scale.

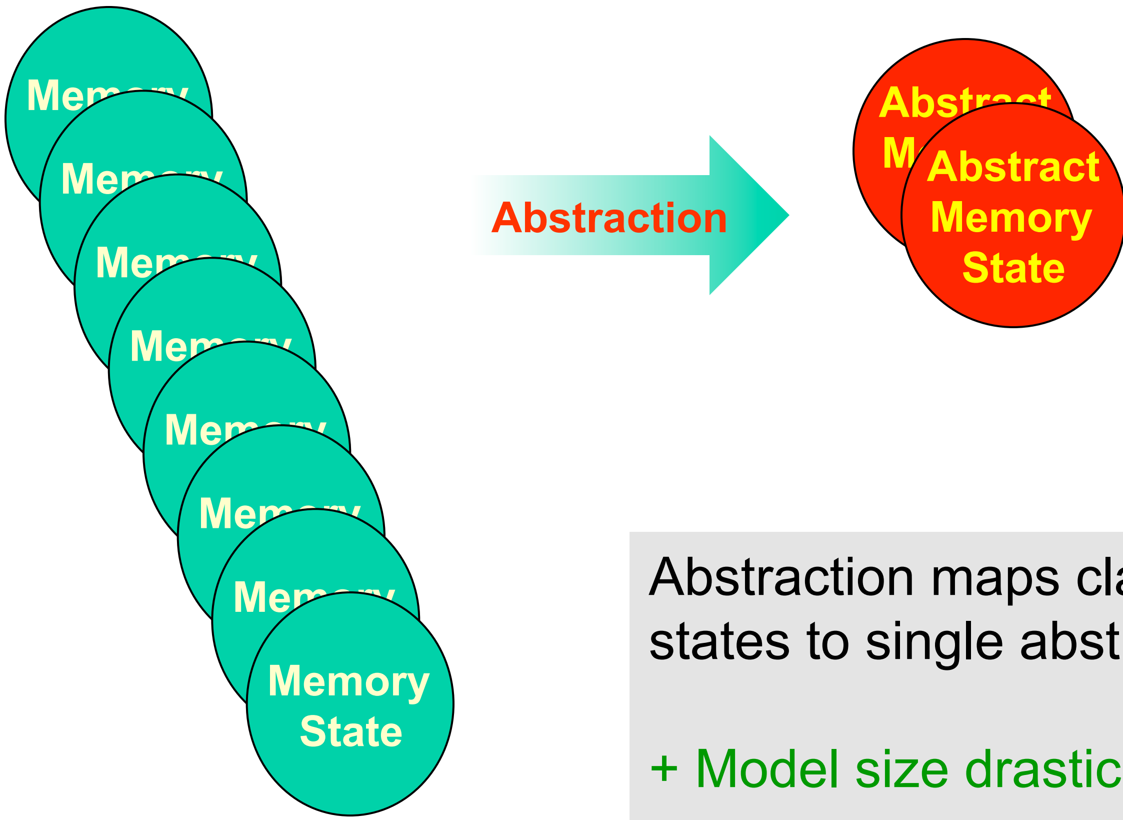
2000s: renewed interest / demand:

Java Pathfinder: NASA Ames
SLAM: Microsoft
Bandera: Kansas State
BLAST: Berkeley
…
SLAM to be shipped to Windows device driver developers.

In general, these tools are unable to handle complex data structures and concurrency.

The MAGIC Tool:

Counterexample-Guided Abstraction Refinement



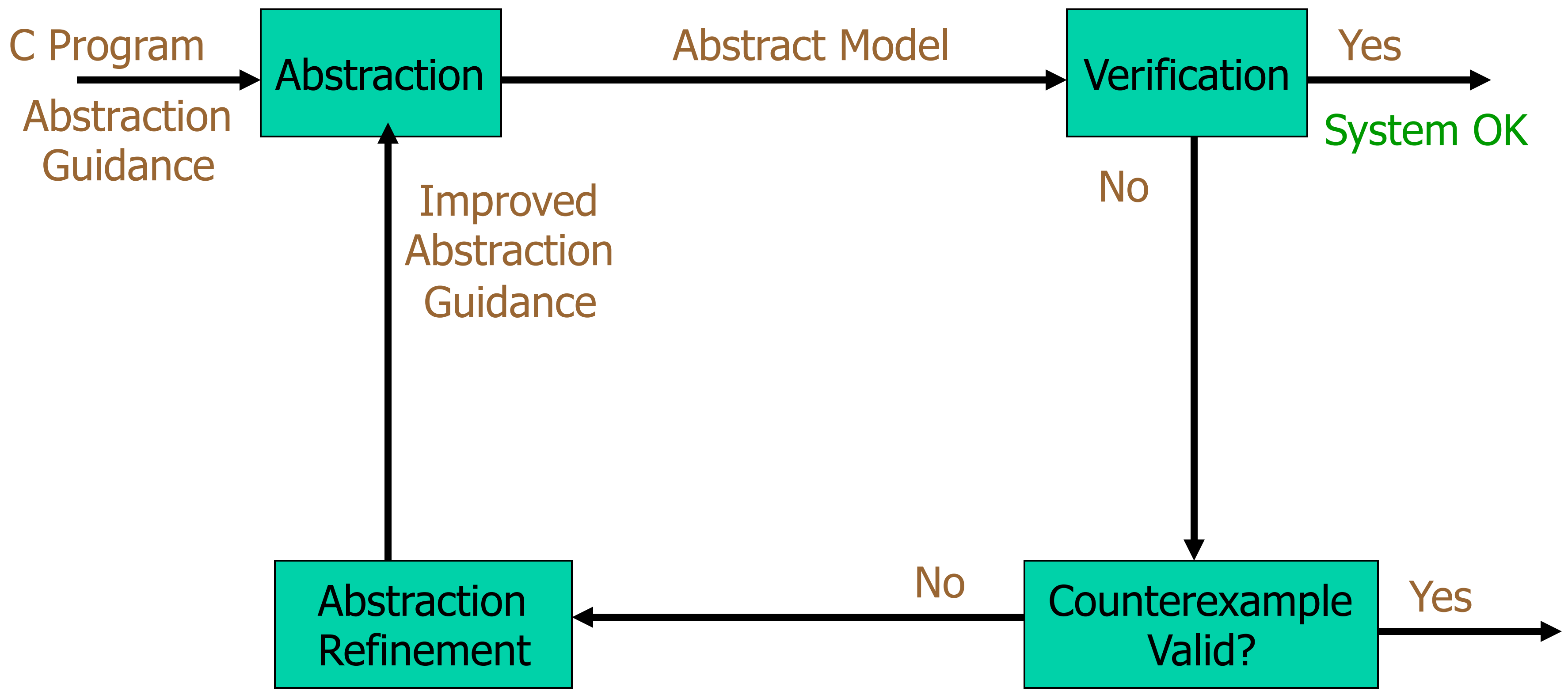
Abstraction maps classes of similar memory states to single abstract memory states.

+ Model size drastically reduced.

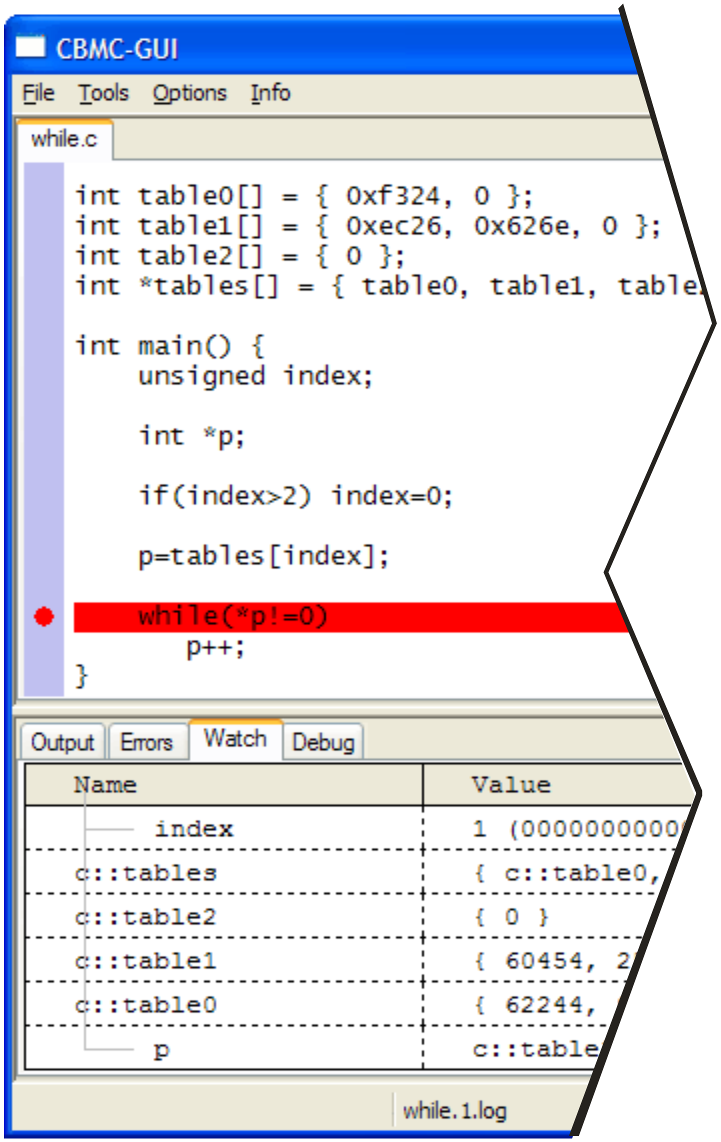
- Invalid counterexamples possible.

The MAGIC Tool:

Counterexample-Guided Abstraction Refinement



CBMC: Embedded Systems Verification



- Method:
  Bounded Model Checking
- Implemented GUI to facilitate tech transfer
- Applications:
  - Part of train controller from GE
  - Cryptographic algorithms (DES, AES, SHS)
  - C Models of ASICs provided by nVidia

Case Study:
Verification of MicroC/OS

- **Real-Time Operating System**
  - About 6000 lines of C code
  - Used in commercial ***embedded systems***
    - UPS, Controllers, Cell-phones, ATMs
- Required **mutual exclusion** in the kernel
  - ***OS_ENTER_CRITICAL()*** and ***OS_EXIT_CRITICAL()***
- **MAGIC** and **CBMC**:
  - Discovered **one unknown bug** related to the locking discipline
  - Discovered three more bugs
  - Verified that **no similar bugs are present**