Weak Memory Models as LLVM-to-LLVM Transformations

Vladimír Štill Petr Ročkai Jiří Barnat

Masaryk University

Brno, Czech Republic

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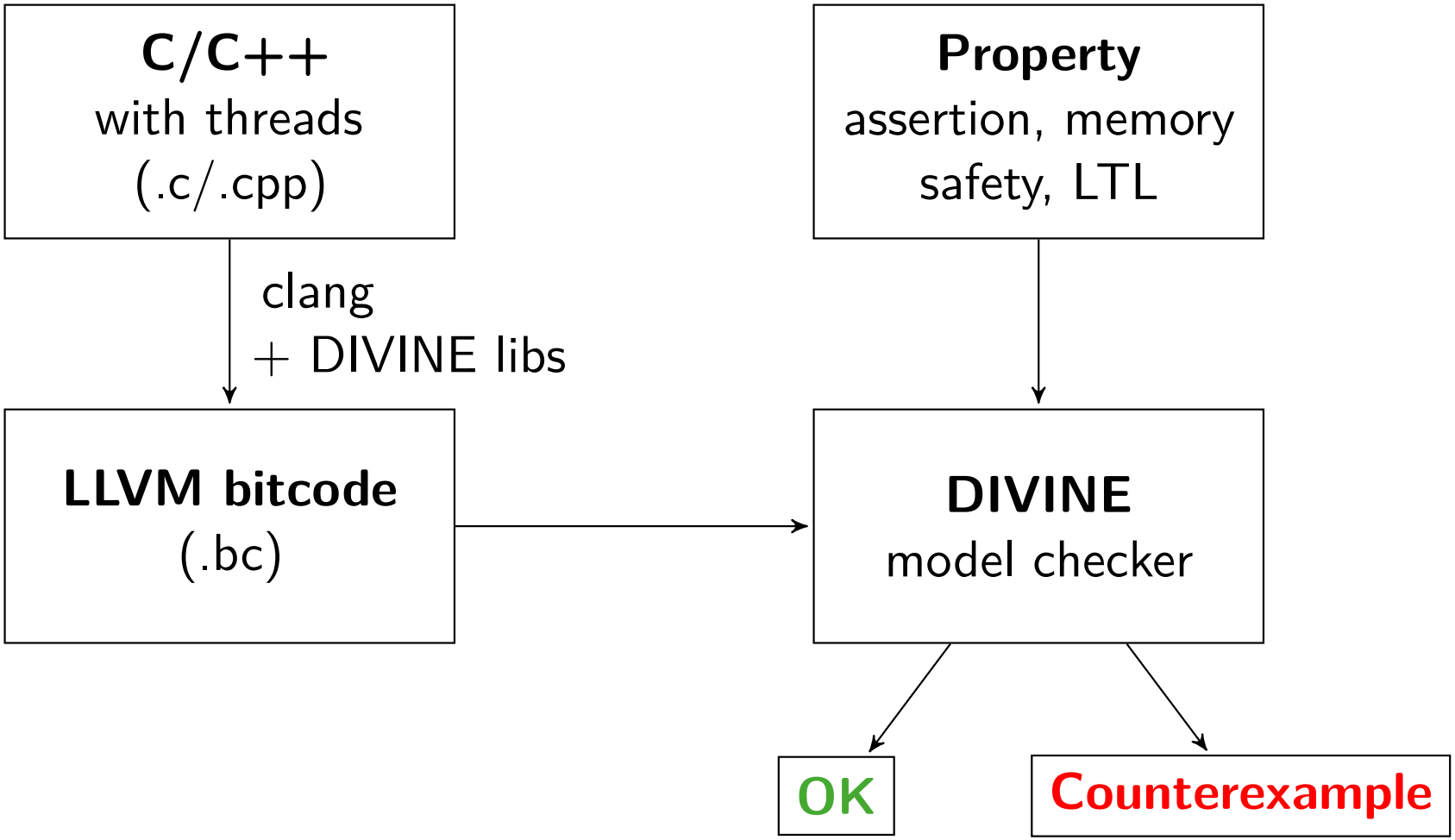
DIVINE model checker

- automated detection of bugs in parallel C++ programs
- verification of assertion/memory safety, LTL specification
- using LLVM bitcode
  - kind of an assembler produced by compilers, such as `clang`
- supports large portions of C++ standard library
- verification of largely unmodified code

Introduction



model checking programs with DIVINE

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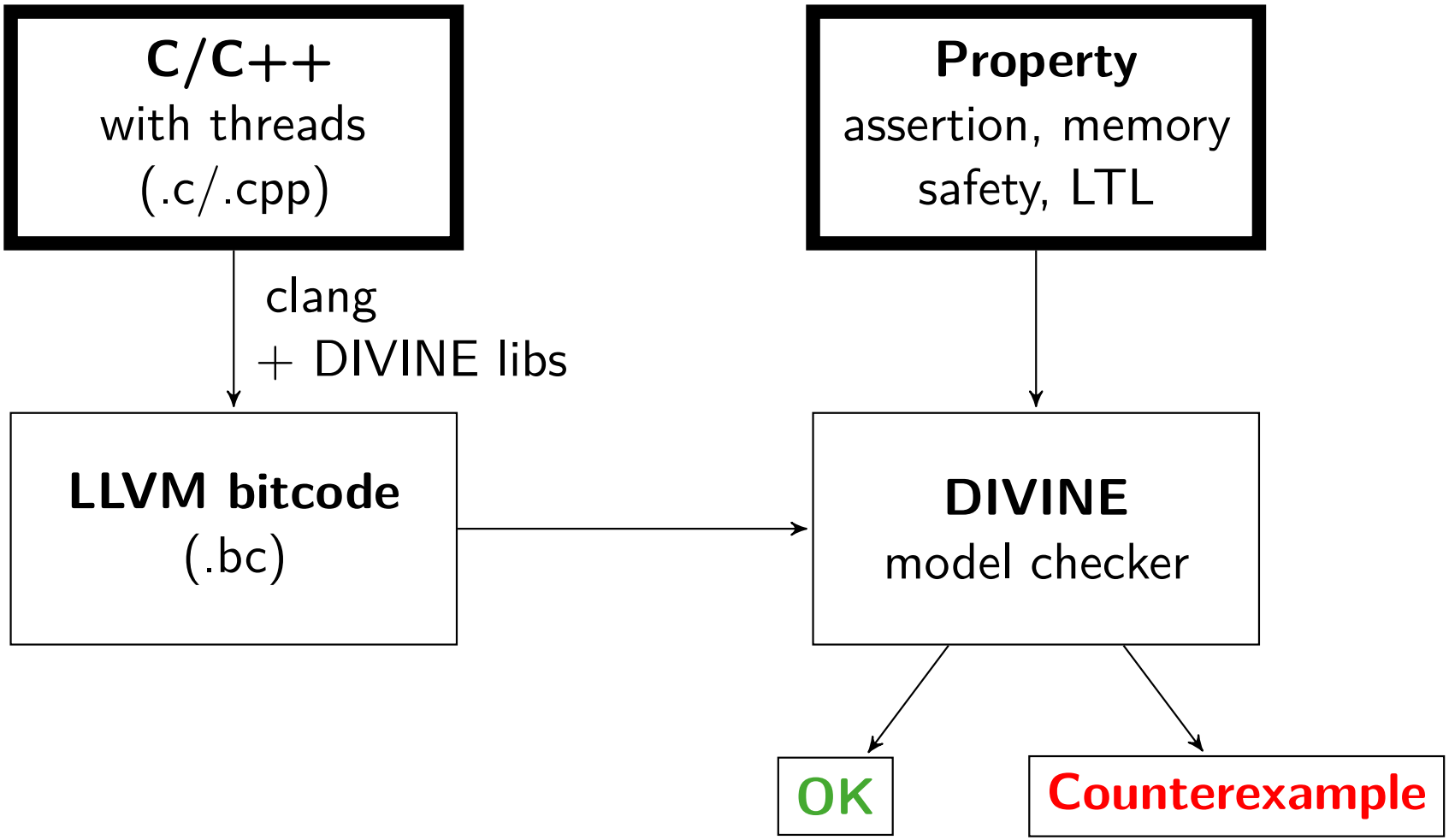

programmer gives inputs: source code and specification

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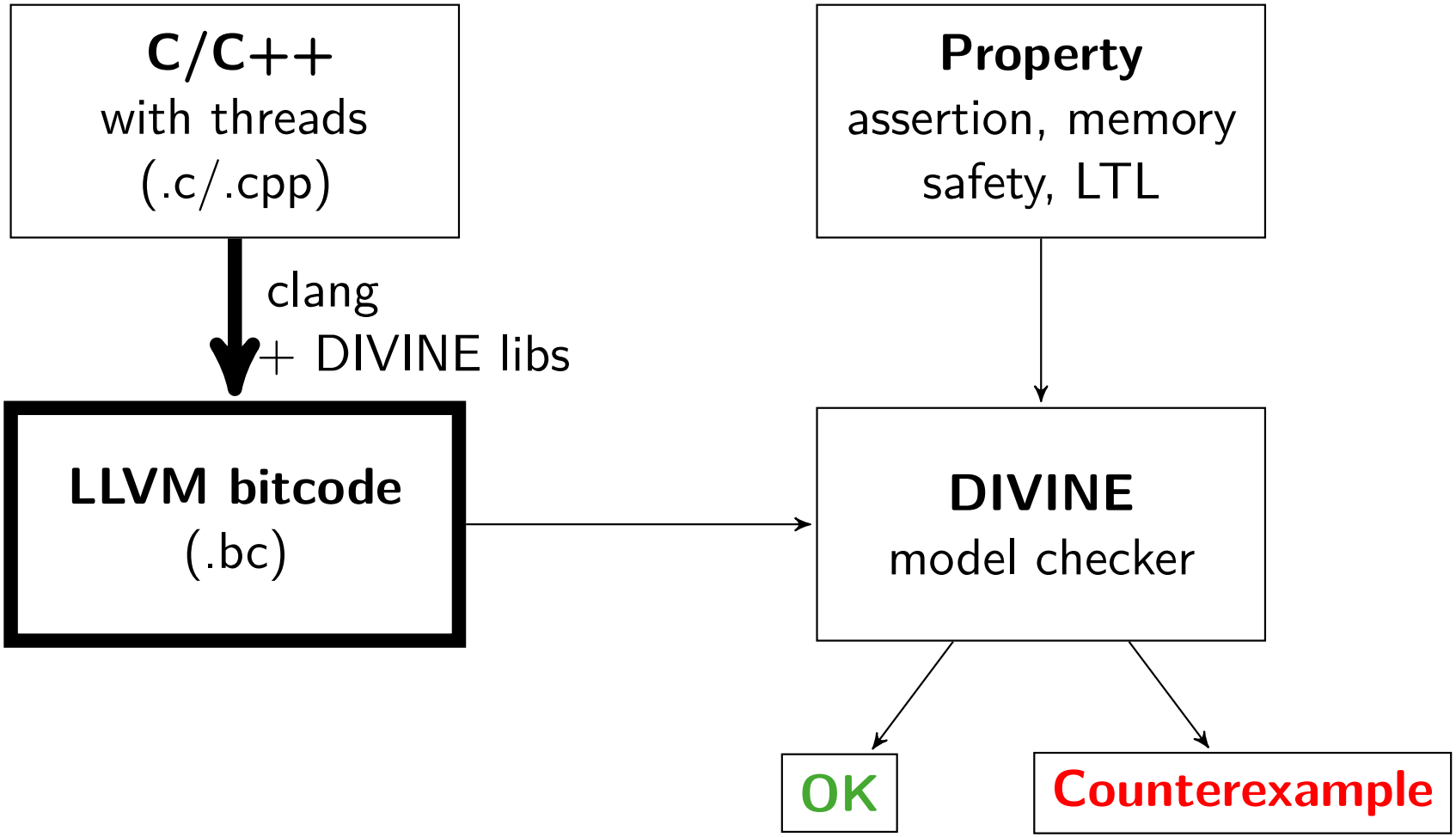

the program is compiled into LLVM bitcode

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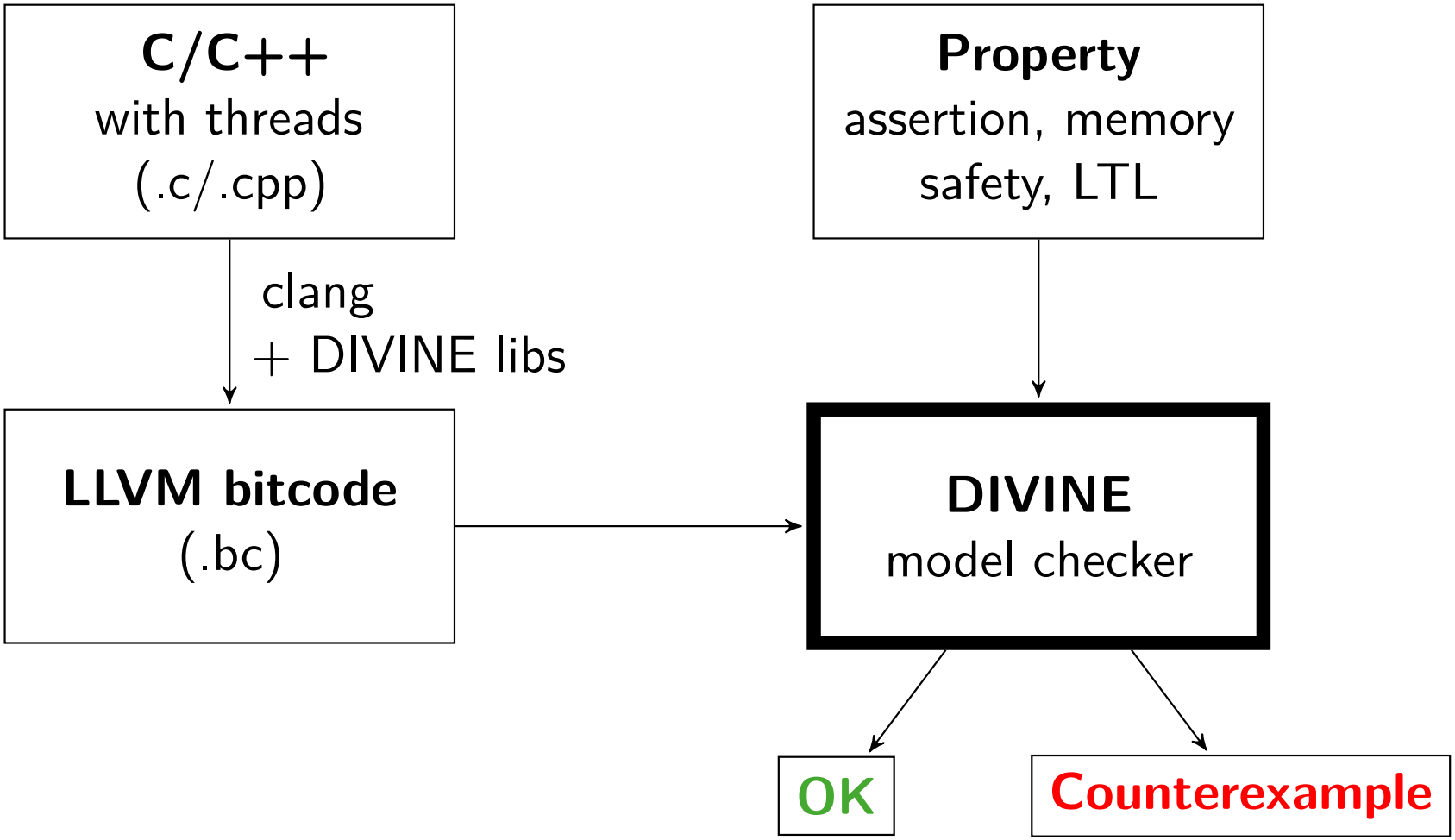

DIVINE explores all relevant interleavings

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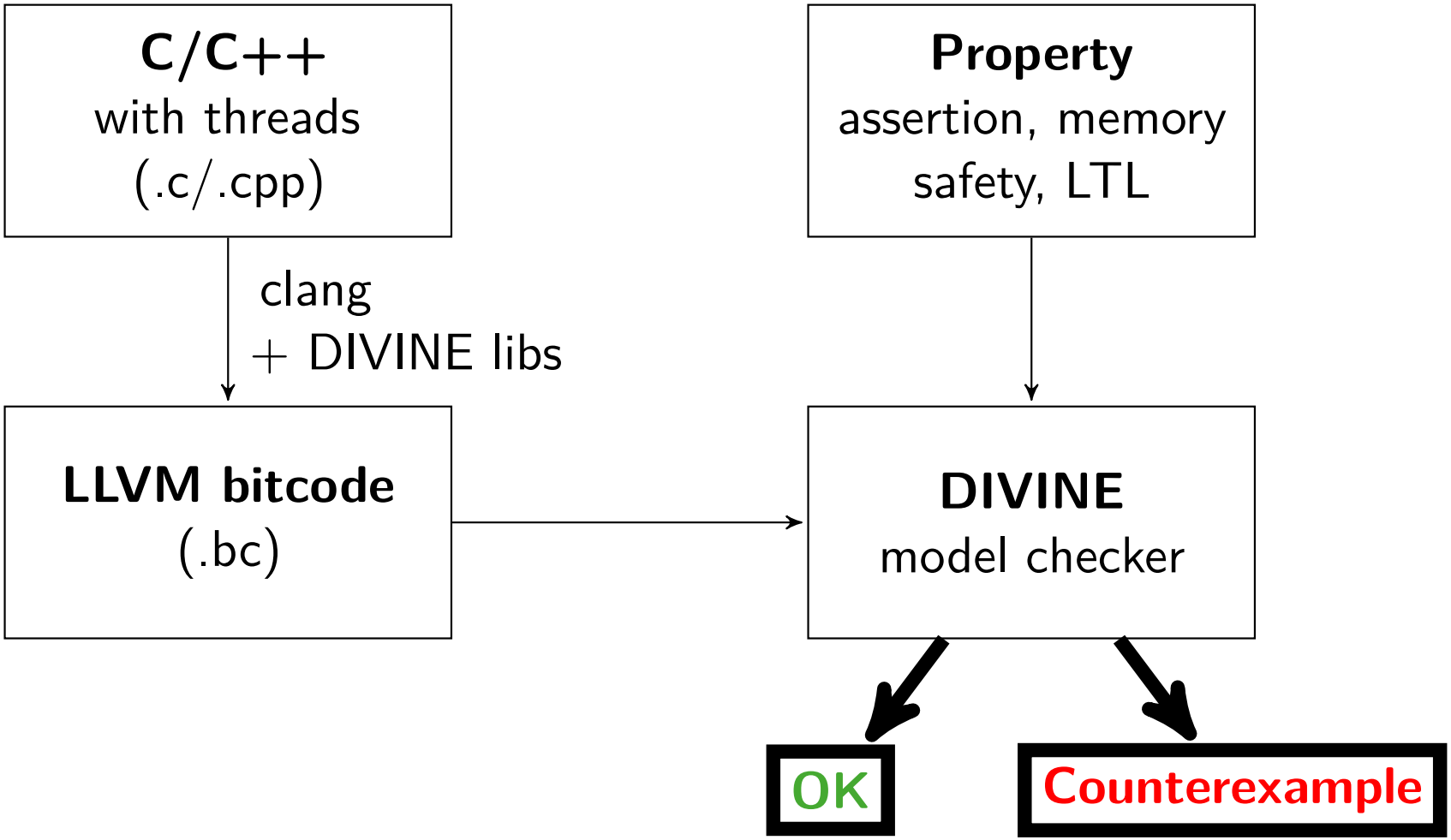

verification results

Explicit-State Model Checking

explores all relevant outcomes of a program

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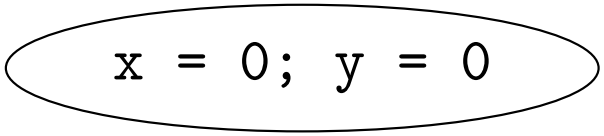

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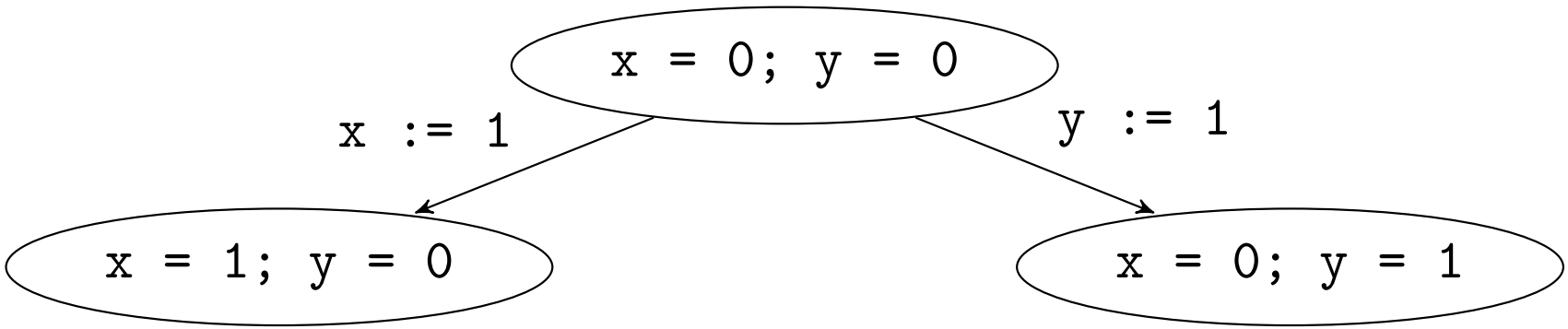

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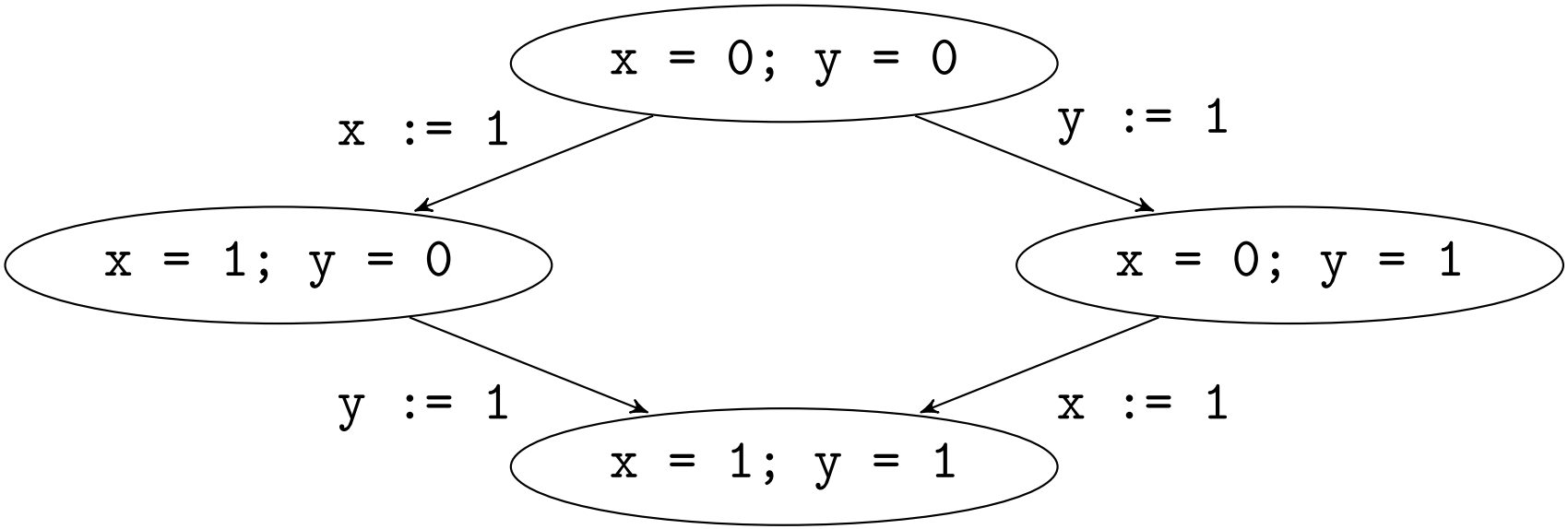

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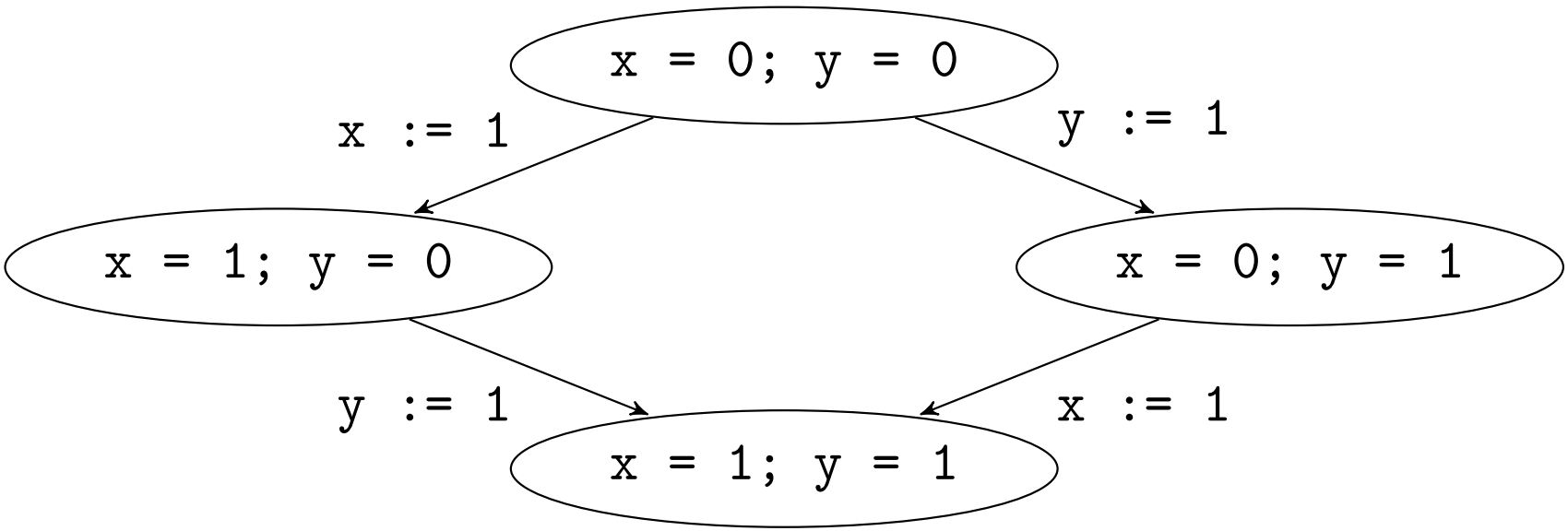

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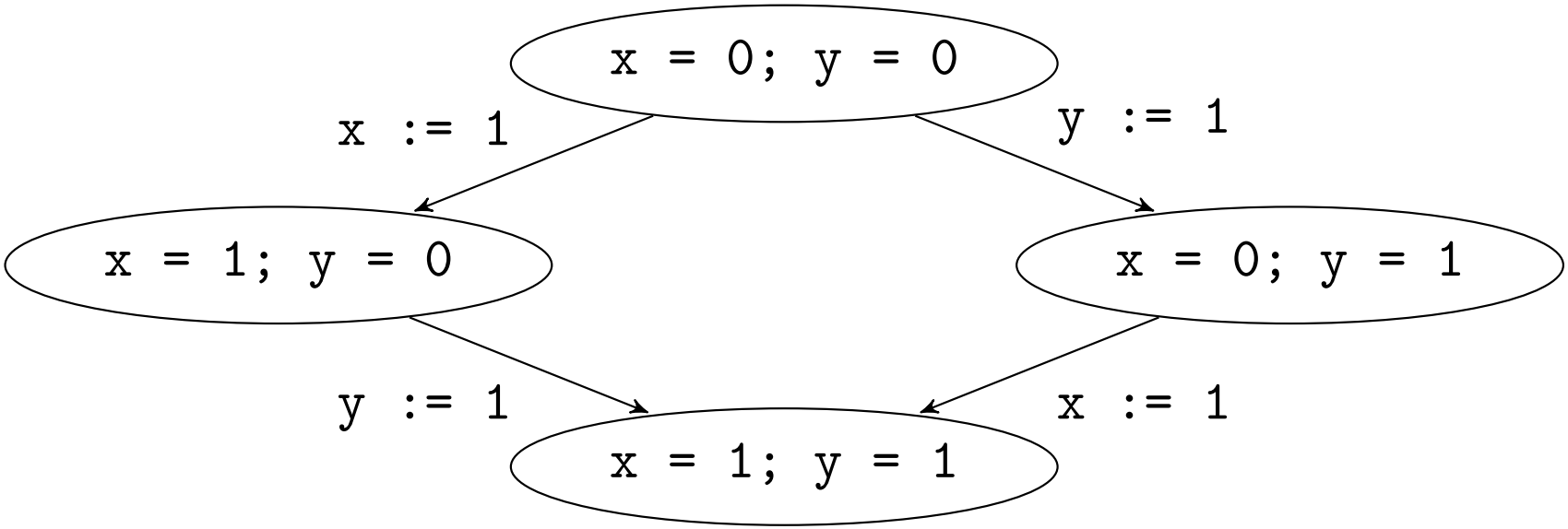

- builds state space
- graph exploration

Demo

Memory Models

- the order of reads and writes in the code does not need to match the order of their execution
  - compiler optimizations
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- verifiers often assume sequential consistency
  - so does DIVINE

C++11 semantics of concurrent access to shared memory

```
int x = 0, y = 0;

void thread1() { x = 1; y = 2; }
void thread2() {
    while ( y == 0 ) { }
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- no guarantees
- `thread2` can read `y` only once
- undefined behaviour

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- no atomicity guarantees
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- can the output be `y = 2` and `x = 0`?
- no, the order of atomic loads and stores is guaranteed to match the order in the source code

Weak Memory Models

many different models on different architectures

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- details can vary between CPUs of the same architecture

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theoretical memory models

- Total Store Order (TSO)
  - similar to the memory model used by x86_64
  - the order of execution of stores is guaranteed to match their order in machine code
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  - the order of execution of stores is guaranteed to match their order in machine code
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- Partial Store Order (PSO)
  - weaker than TSO
  - independent stores can be reordered too
  - enables more optimizations

Weak Memory Models

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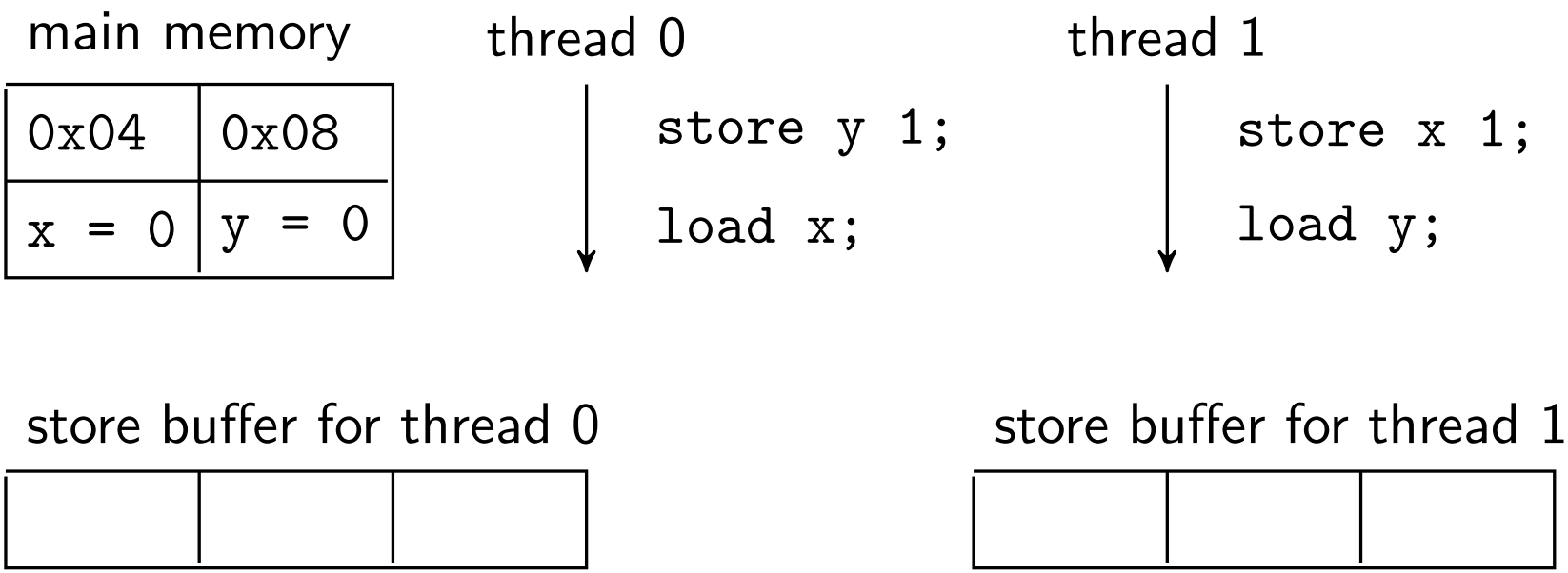
Total Store Order can be simulated using store buffers:



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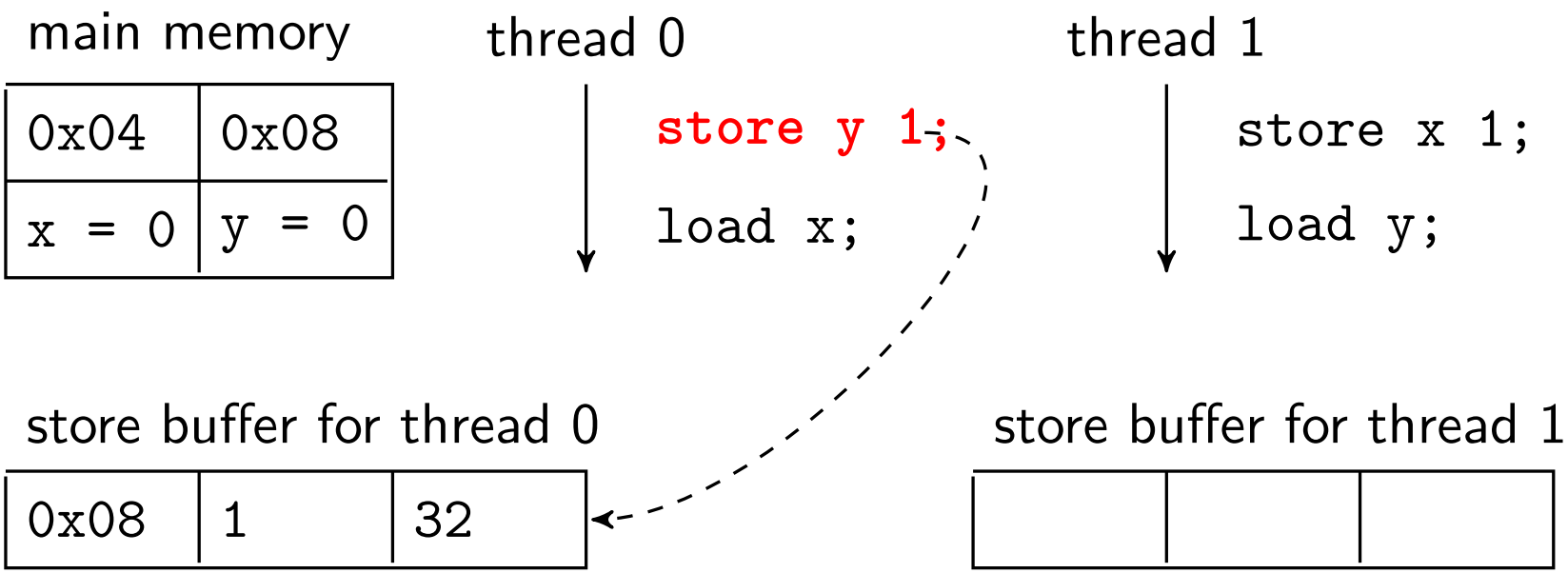

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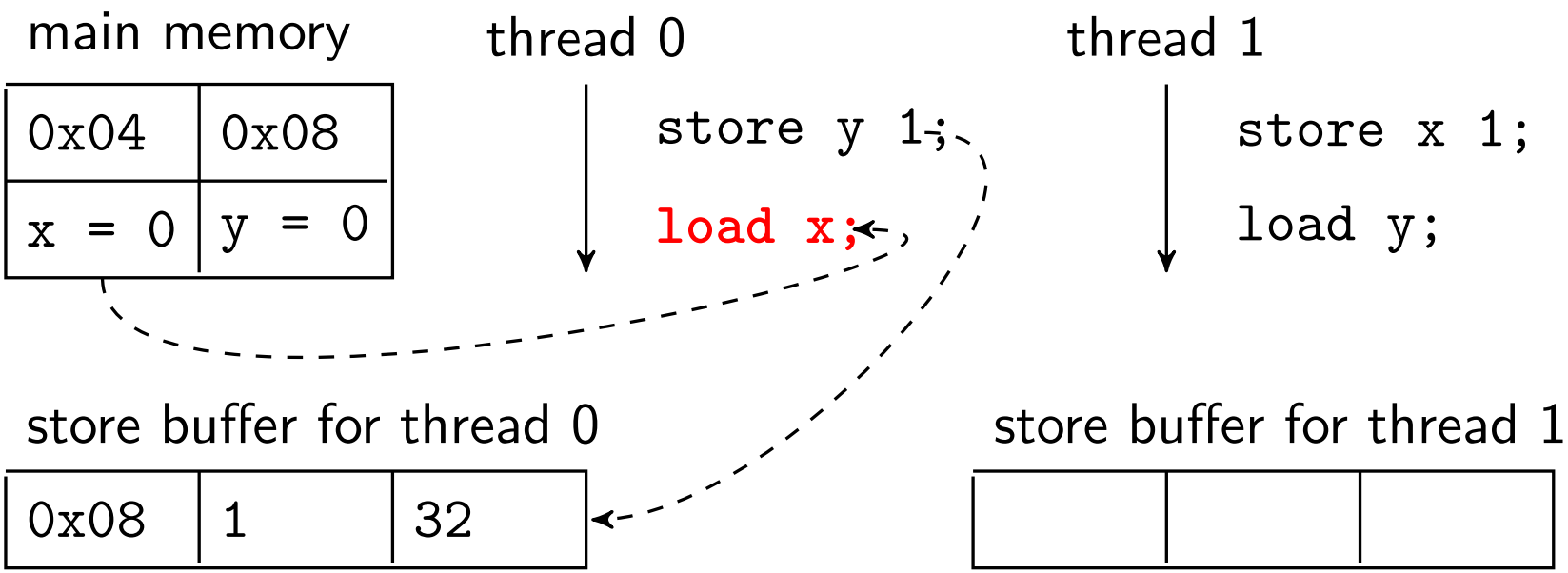

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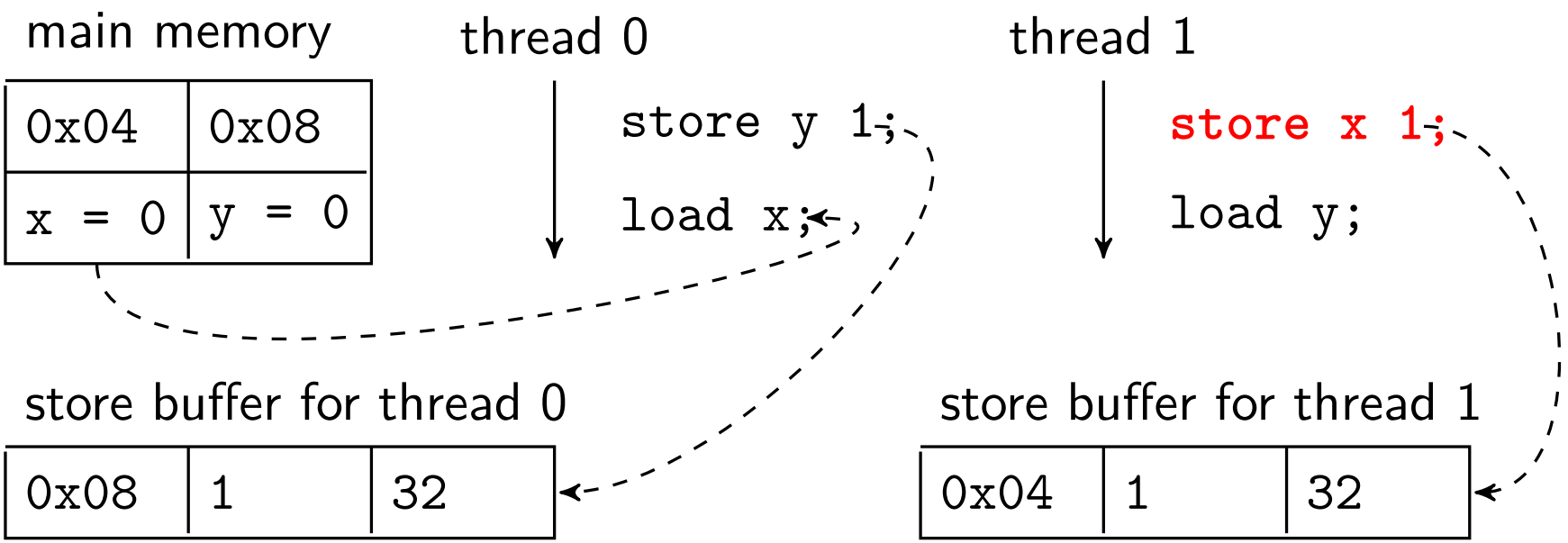

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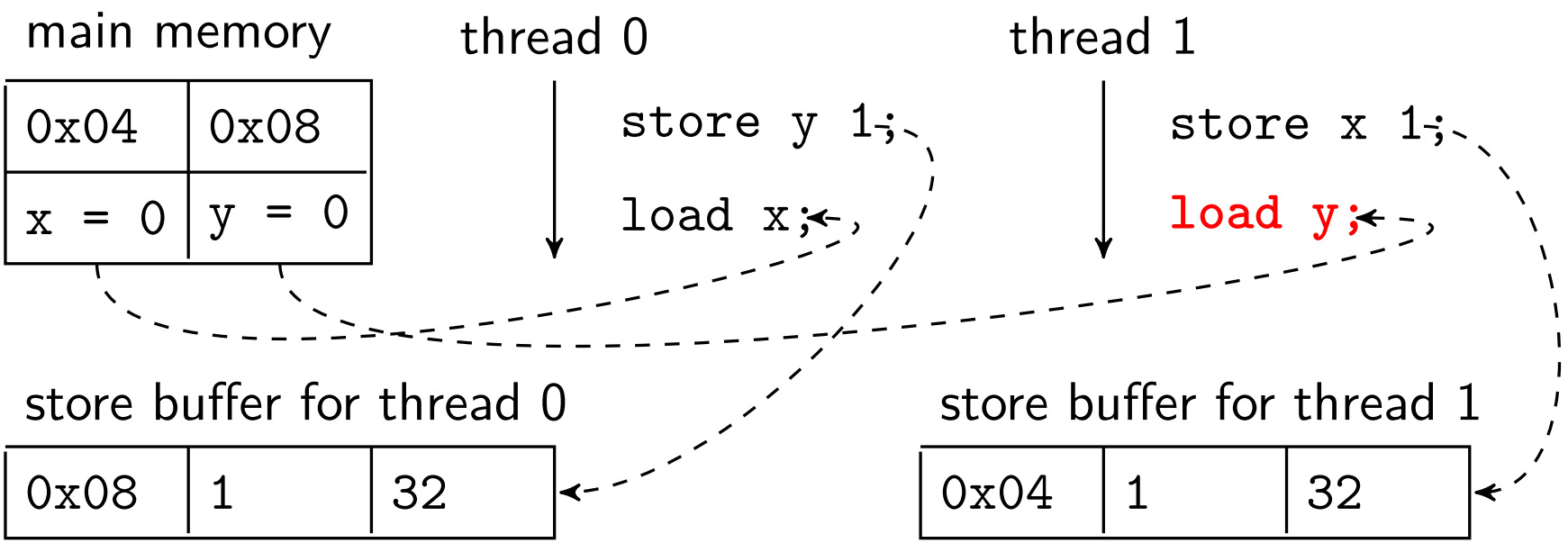
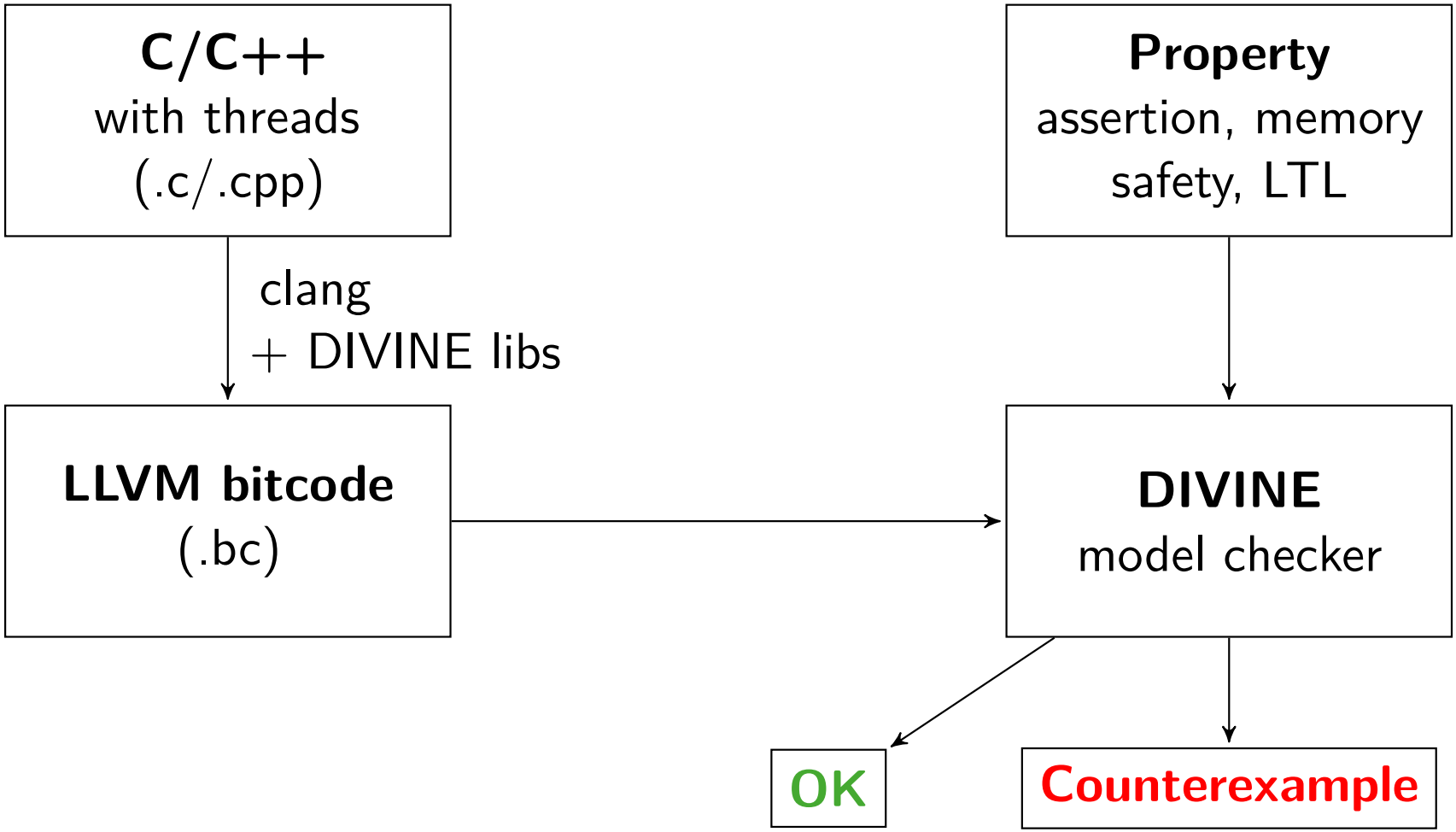


Weak Memory Models as Transformation



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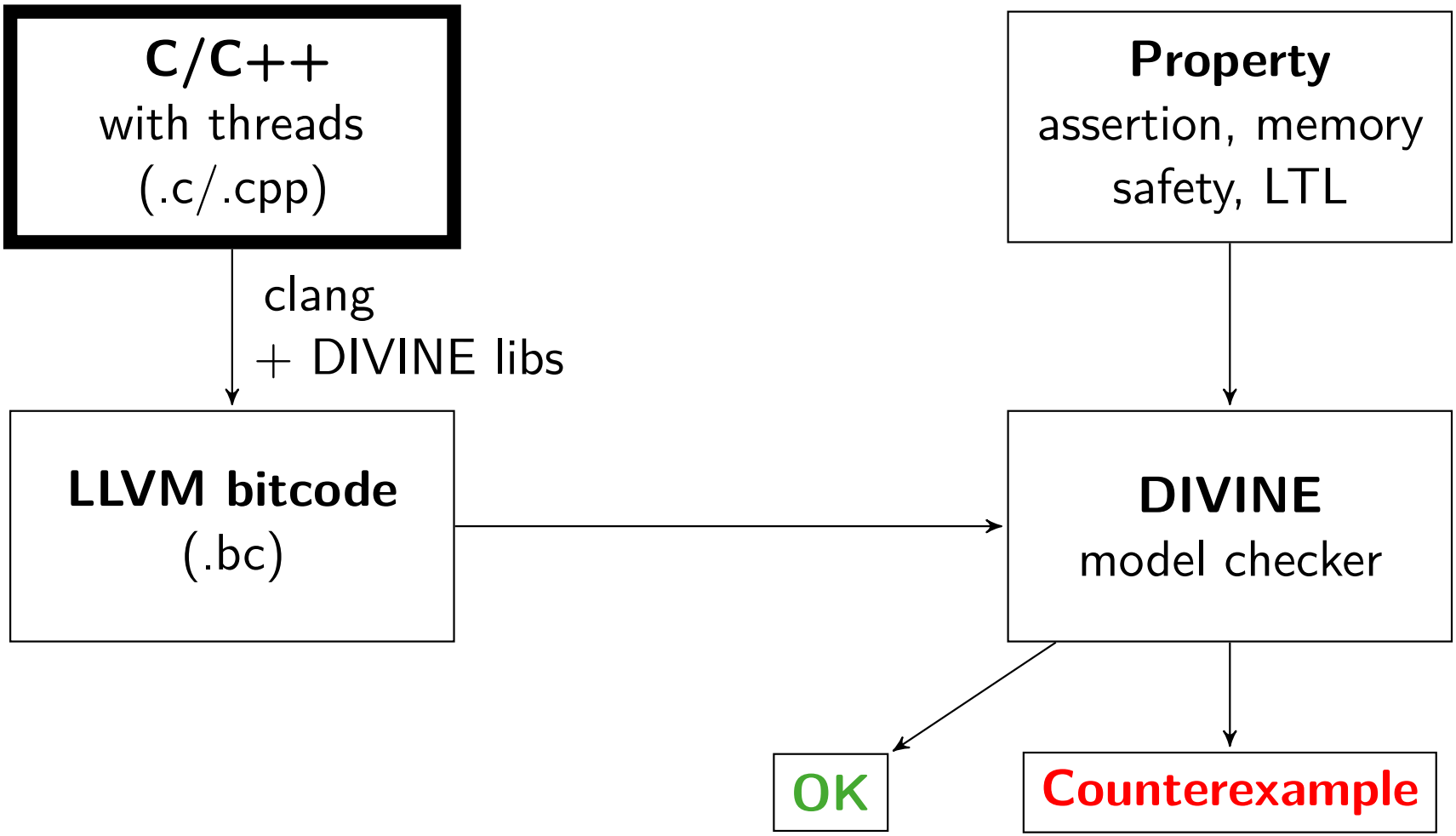

input program does not specify the memory model exactly

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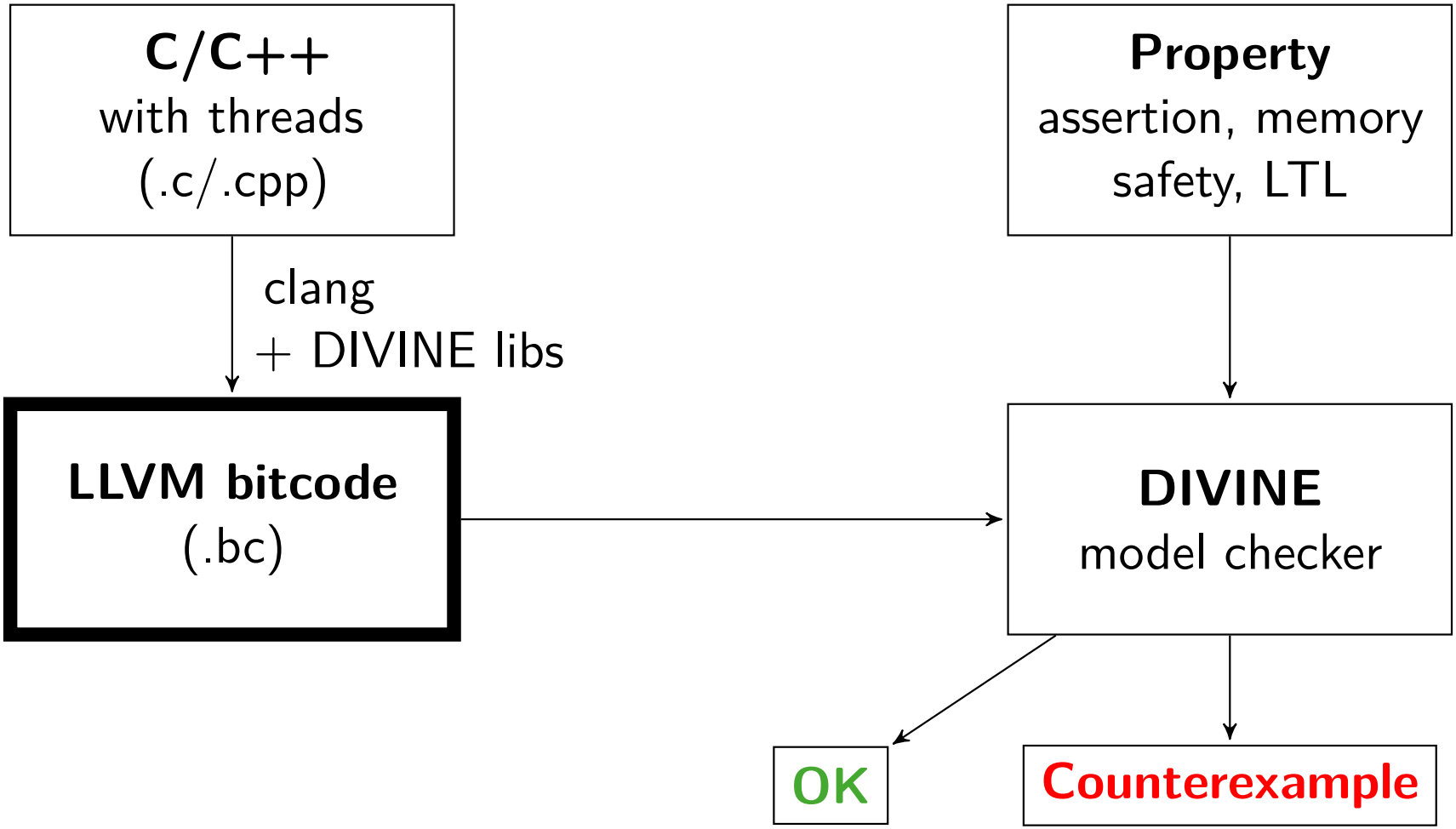

LLVM roughly copies the C++11 memory model

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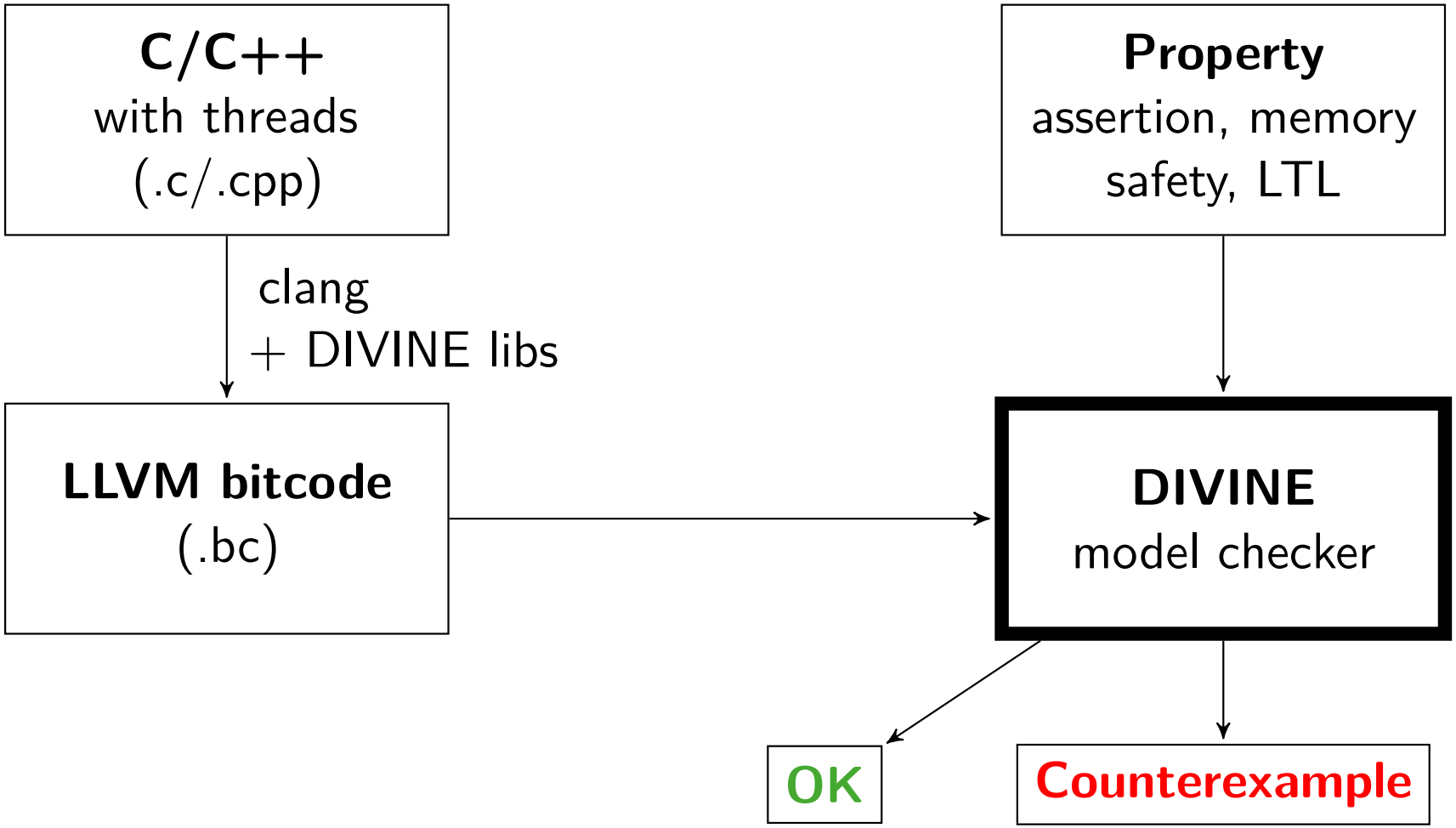

DIVINE assumes sequential consistency

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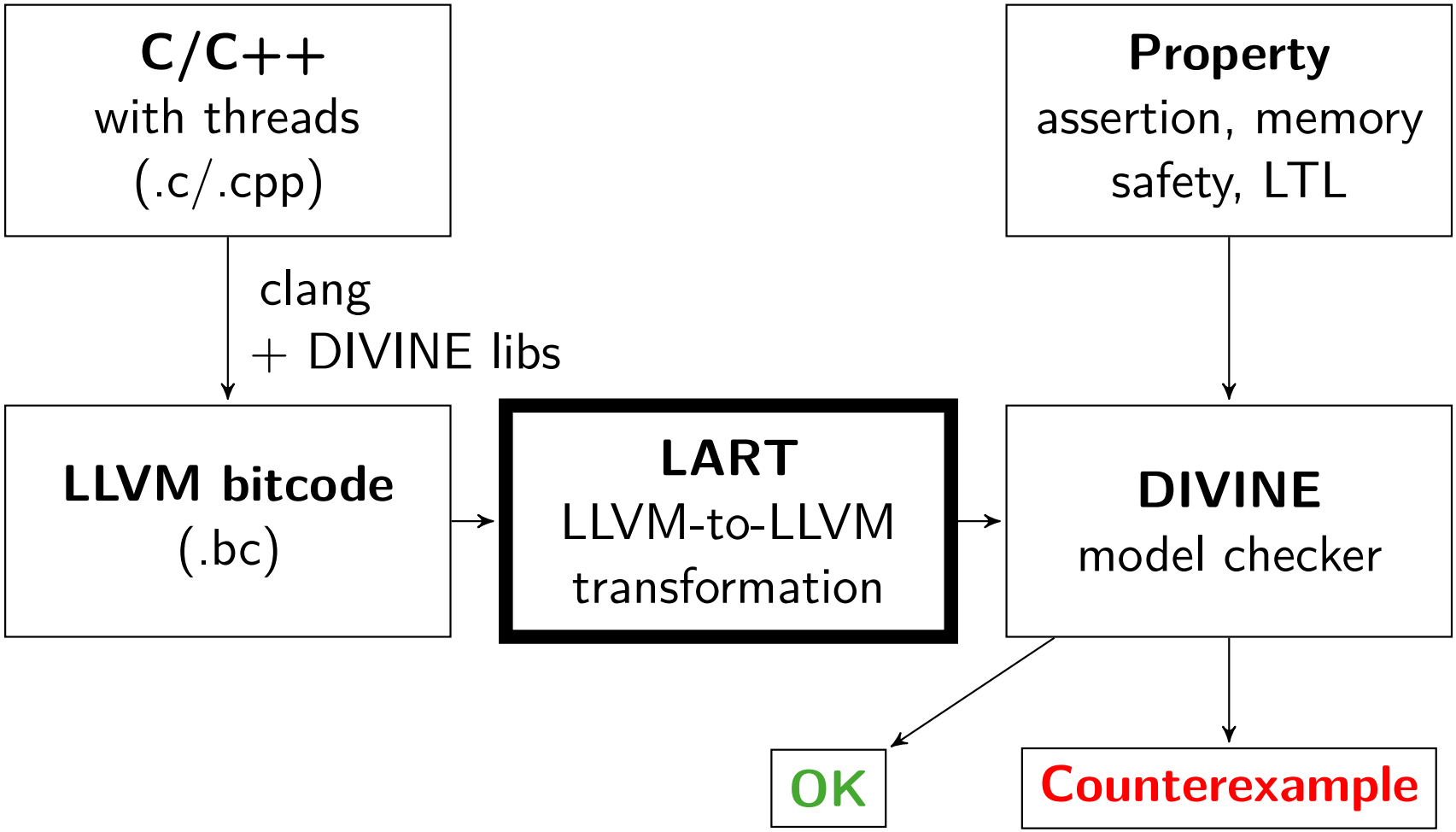

LART instruments LLVM bitcode based on a relaxed memory model

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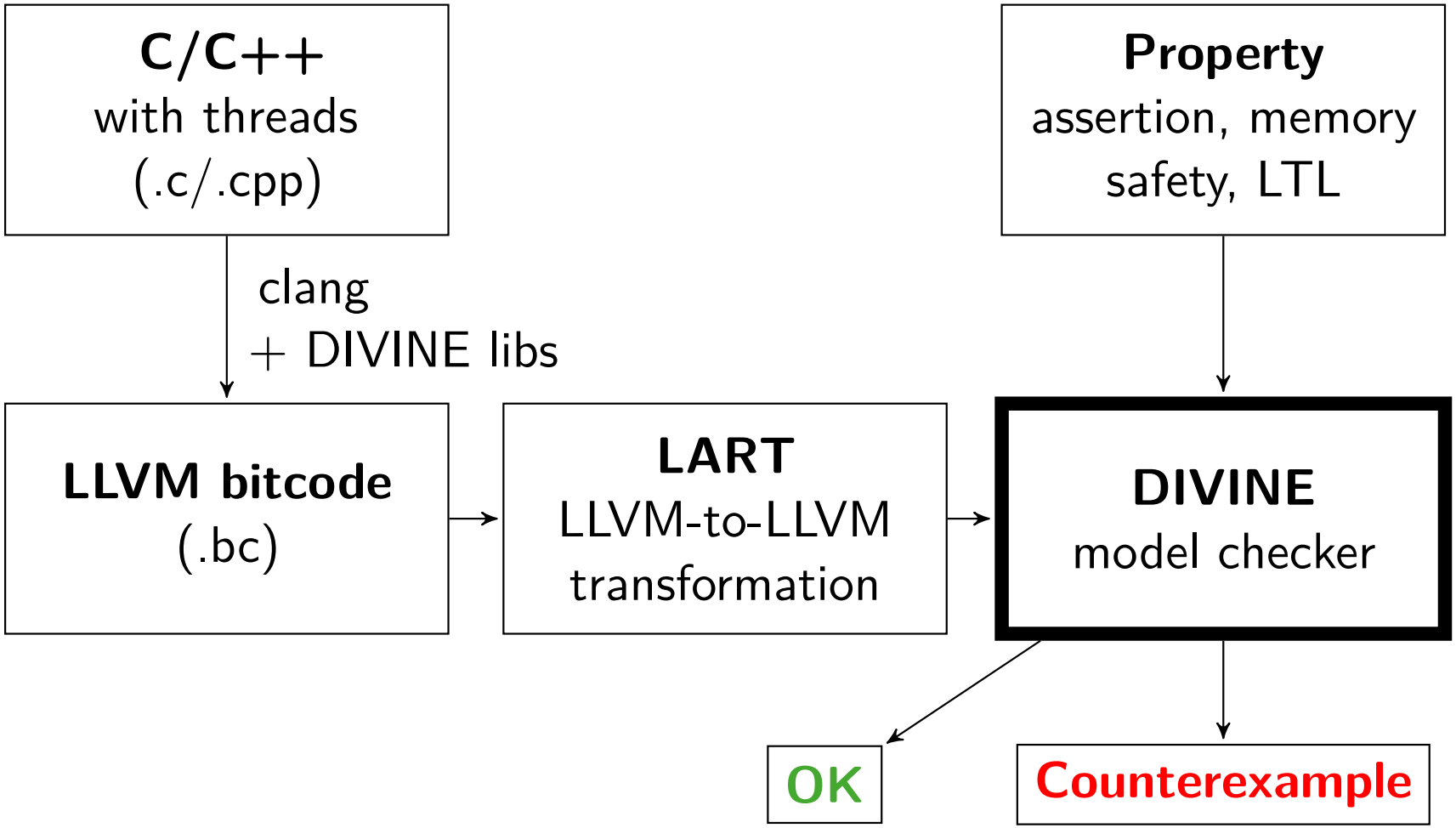

the model is now verified assuming the relaxed memory model

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  - integrates well with explicit-state model checker like DIVINE

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  - API for transformations
  - an ecosystem of code generators for many languages
  - analysis tools other than DIVINE can use this transformation

The Transformation

memory-manipulating instructions need to be replaced to enable TSO simulation

- add a store buffer for each thread
- `store` instructions save data to the store buffer
- `load` instructions first look up data in the local store buffer, then in memory
- `fence` (memory barrier) instructions flush the store buffer
- atomic instructions and memory-manipulating functions such as `memcpy` needs to be handled
- buffers are flushed nondeterministically

Infinite Delay Problem

$\varphi = FG(\neg w_0 \wedge \neg w_1)$

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bool x = false, y = false;
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2    y = true;
3    while (!x) { AP(w0); }
4    for (;;) { /*work*/ }
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Solution

- for each program thread, we add a dedicated flushing thread
- we use weak fairness to avoid infinite delays

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- currently not implemented
  - DIVINE cannot verify memory safety with TSO currently

Demo

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- with TSO simulation, every load and store is visible
  - this makes reduction inefficient
- thread-local memory does not need to be stored in a store buffer

Experimental Results

model	buffer size	assertion found	# of states	reduced # of states	memory [GB]	time [s]
`simple_sc`	N/A	no	205	N/A	0.16	1
`simple_mtso`	1	**yes**	6.89 k	N/A	0.17	3
`simple_stso`	1	**yes**	10.7 k	10.7 k	0.17	6
`simple_tso`	1	**yes**	24.7 M	537.2 k	3.18	20318
`peterson_sc`	N/A	no	1.68 k	N/A	0.16	1
`peterson_tso`	0	no	55.9 k	N/A	0.17	38
`peterson_tso`	2	**yes**	2.86 M	95.7 k	0.79	990
`peterson_tso`	3	**yes**	4.70 M	129.9 k	1.21	1610
`fifo_sc`	0	no	6951	N/A	0.73	20
`fifo_tso`	1	no	–	44 M	–	–

Conclusion

- fully automatic instrumentation of LLVM bitcode with Total Store Order approximation
- enables TSO verification in DIVINE or other verifiers which assume Sequential Consistency
- verification of assertion safety and LTL properties
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- better state space reductions

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