Hunting Bugs
In Multithread C Programs

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Finding Bugs in Software

- testing is still the most used approach in industry
  - can be slow, expensive, resource-consuming
  - no confidence that there are no missed bugs, or no bugs at all

- manual source-code inspection can spot very subtle bugs
  - inefficient, error-prone, unfeasible on big programs

- automatic source-code analysis is generally undecidable **[Church 1936] [Turing 1936]**
  - approximation: missed bugs *vs* false positives
  - restrictions: focus on *specific classes of programs* and *specific checks*
    (array bounds, division-by-zero, assertion violation, …)

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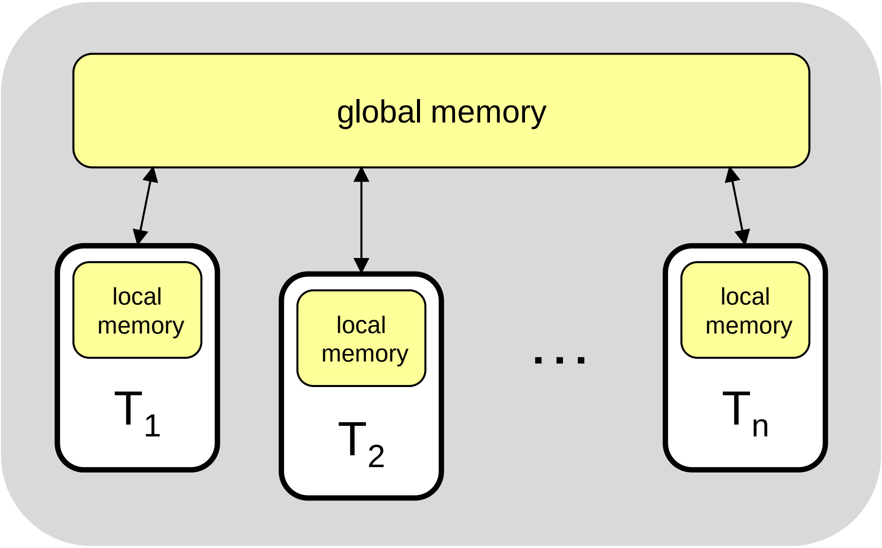
we focus on

automatic analysis of

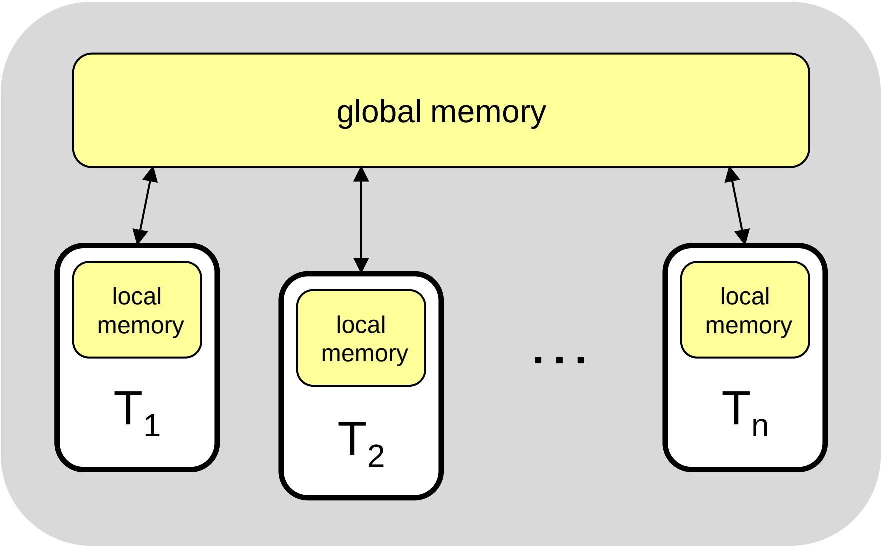
→ **multithread C programs** ←

(reachability + assertion violation)

Multithread Programs

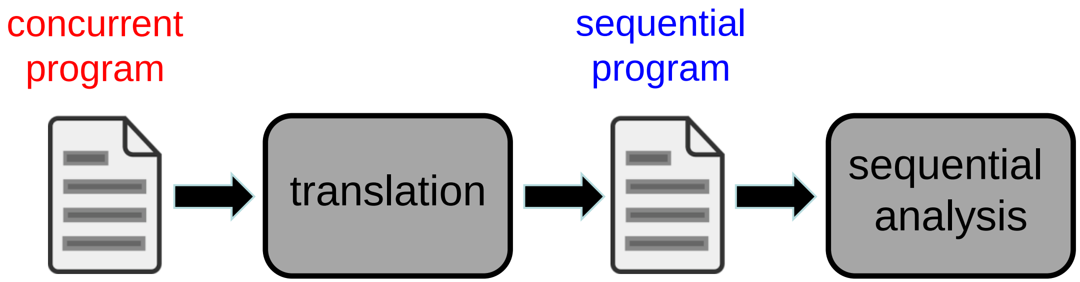


Multithread Programs

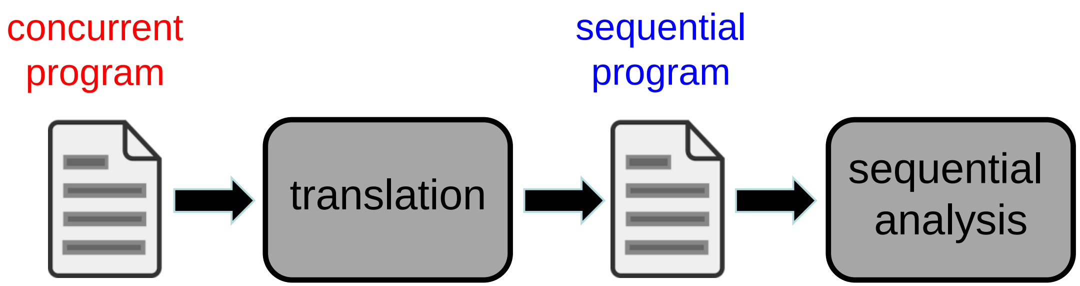


- harder development
  - thread interference must be considered
  - concurrency introduces further errors (e.g. deadlock)
- harder analysis
  - #interleavings exponential in (#threads x #statements)
  - testing not effective
  - gap with tools for sequential programs

Sequentialization

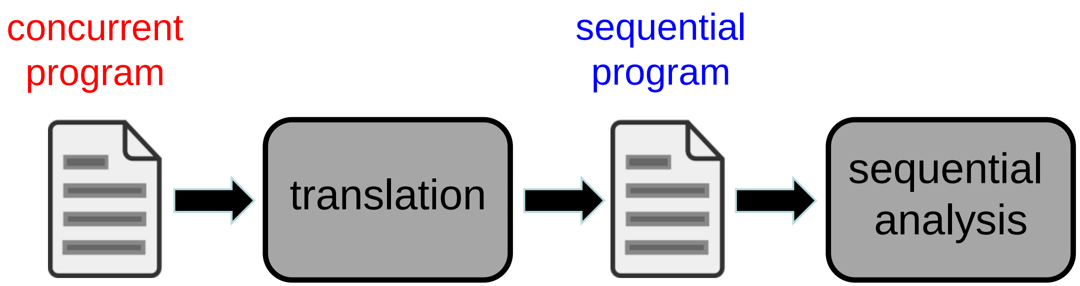


Sequentialization



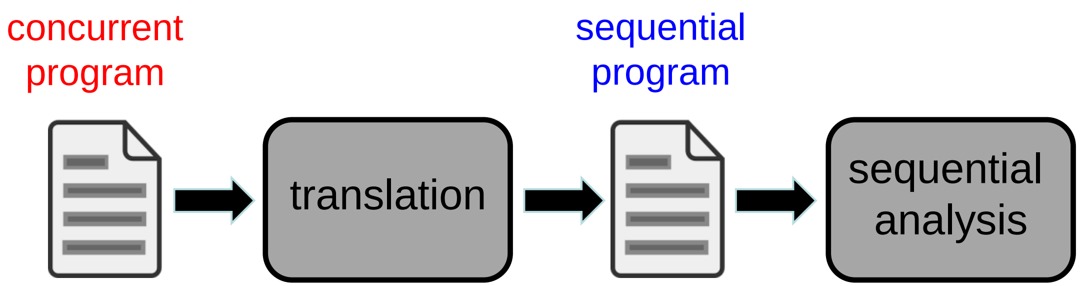
- convenience
  - re-use industrial-strength existing tools as backends
  - fast prototyping (designers can concentrate on concurrency)
  - can work with different backends

Sequentialization



- known sequentializations
  - initially proposed for up to 2 context-switches [Qadeer,Wu PLDI2004]
  - generalised to *k* round-robin context-switches [Lal,Reps CAV2008]
    - no dynamic memory allocation, dynamic thread creation, limited backend integration
    - implemented for C programs [Lahiri,Qadeer,Rakamaric CAV2009] [Fischer,Inverso,Parlato ASE2013]
  - *k* context-switches, lazy sequentialization [La Torre,Madhusudan,Parlato CAV2009]
    - not good for bounded model-checking backends
    - implemented for Boolean programs

Sequentialization



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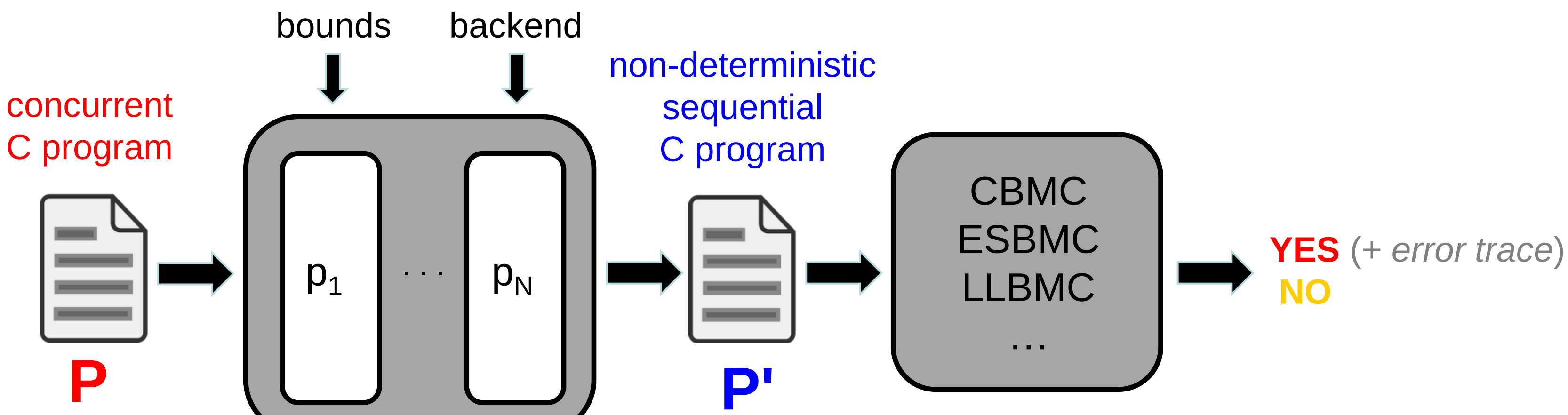
→ too many limitations both <u>in the schema</u> and <u>in the tool</u> ←

CSeq Sequentialization Framework

is a bug reachable in program **P** within the given bounds?



- **schema I**: lazy context-bounded analysis (bounds no. of context-switches)
  Lazy-CSeq tool [Inverso,Tomasco,Fischer,La Torre,Parlato TACAS-SVCOMP2014,CAV2014]

- **schema II**: memory-unwinding (bounds no. of shared memory writes)
  MU-CSeq tool [Tomasco,Inverso,Fischer,La Torre,Parlato TACAS-SVCOMP2014]

Schema I:
Lazy
Sequentialization
(Lazy-CSeq)

Lazy-CSeq Sequentialization

Translation **P** ⇝ **P'**:

- unwinding, inlining
- thread **T** ⇝ function **T'**
- main driver:
  - ▹ for round in [1..K]
  - ▹ for thread in [1..N]
  - ▹ $\mathbf{T'_{thread}}$ ();

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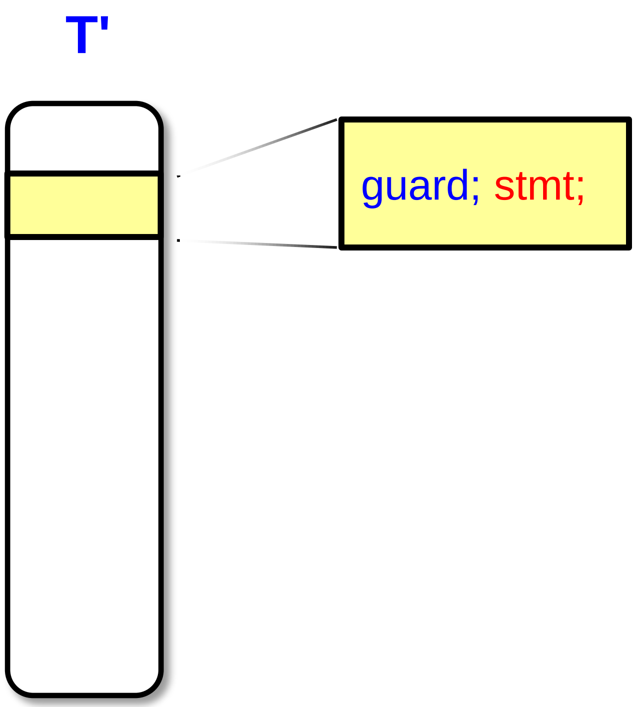
Thread **T** ⇝ function **T'**

- var x; ⇝ static var x; // persistency
- stmt; ⇝ guard; stmt; // context-switch



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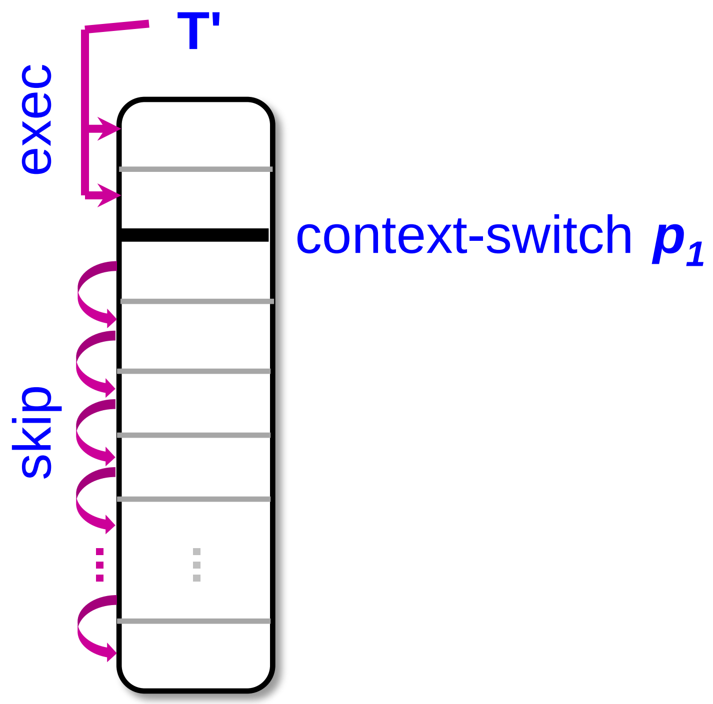
Thread **T** ⇝ function **T'**

- var x; ⇝ static var x;
- stmt; ⇝ guard; stmt;

Thread simulation: **round 1**

- guess context-switch point p_1
- execute stmts before p_1
- jump in mult. hops to the end



simulation round 1

Lazy-CSeq Sequentialization

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- main driver:
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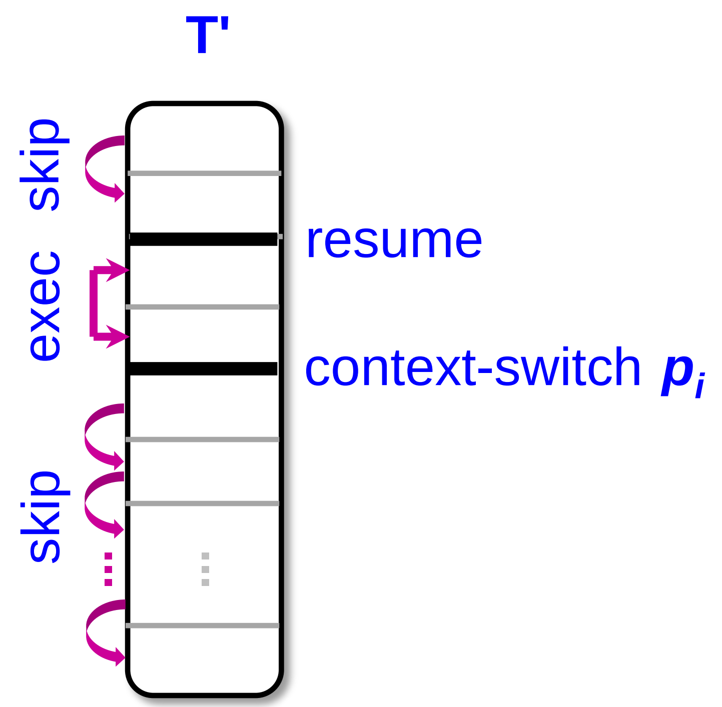
Thread **T** ⇝ function **T'**

- var x; ⇝ static var x;
- stmt; ⇝ guard; stmt;

Thread simulation: **round *i***

- guess context-switch point p_i
- execute stmts from p_{i-1} to p_i
- jump in mult. hops to the end



simulation round *i* >1

Lazy-CSeq Example

```
pthread_mutex_t m; int c=0;
void P(void *b) {
  int tmp=(*b);
  pthread_mutex_lock(&m);
  if(c>0)
    c++;
  else {
    c=0;
    while(tmp>0) {
      c++; tmp--;
    }
  }
  pthread_mutex_unlock(&m);
}
void C() {
  assume(c>0);
  c--;
  assert(c>=0);
}
int main(void) {
  int x=1,y=5;
  pthread_t p0,p1,c0,c1;
  pthread_mutex_init(&m);
  pthread_create(&p0,P,&x);
  pthread_create(&p1,P,&y);
  pthread_create(&c0,C,0);
  pthread_create(&c1,C,0);
  return 0;
}
```

concurrent

analysis on the sequential program:

- fast bug finding
- low memory usage

```
bool active[T]={1,0,0,0,0};
int cs,ct,pc[T],size[T]={5,8,8,2,2};
#define G(L) assume(cs>=L);
#define J(A,B) if(pc[ct]>A||A>=cs) goto B;
pthread_mutex_t m; int c=0;
void P0(void *b) {
 0:J(0,1) static int tmp=(*b);
 1:J(1,2) pthread_mutex_lock(&m);
 2:J(2,3) if(c>0)
 3:J(3,4)   c++;
          else { G(4)
 4:J(4,5)   c=0;
            if(!(tmp>0)) goto _l1;
 5:J(5,6)   c++; tmp--;
            if(!(tmp>0)) goto _l1;
 6:J(6,7)   c++; tmp--;
            assume(!(tmp>0));
            _l1: G(7);
          } G(7)
 7:J(7,8) pthread_mutex_unlock(&m);
          goto _P0; _P0: G(8)
 8:        return;
}
void P1(void *b) {...}
void C0() {
 0:J(0,1) assume(c>0);
 1:J(1,2) c--;
          assert(c>=0);
          goto _C0; _C0: G(2)
 2:        return;
}
void C1() {...}
int main0() {
          static int x=1,y=5;
          static pthread_t p0,p1,c0,c1;
 0:J(0,1) pthread_mutex_init(&m);
 1:J(1,2) pthread_create(&p0,P0,&x,1);
 1:J(2,3) pthread_create(&p1,P1,&y,2);
 2:J(3,4) pthread_create(&c0,C0,0,3);
 3:J(4,5) pthread_create(&c1,C1,0,4);
          goto _main; _main: G(4)
 5:        return 0;
}
int main() {...see Fig. 4...}
```

```
void main(void) {
 for(r=1; r<=K; r++) {
  ct=0;
  // only active threads
  if(active[ct]) {
   // next context switch
   cs=pc[ct]+nondet_uint();
   // appropriate value?
   assume(cs<=size[ct]);
   // thread simulation
   fseq_0(arg[ct]);
   // store context switch
   pc[ct]=cs;
  }
  .........
  ct=n;
  if(active[ct]) {
   .........
}}}
```

sequential

Schema II:
Memory-unwound Sequentialization
(MU-CSeq)

Sequentialization of Concurrent Programs

Basic Idea:

convert concurrent programs into *equivalent* sequential programs

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Mu-CSeq Approach:

Pc ⇝ M : Ps

- **M** is a guessed sequence of write operations into the shared memory
- **Ps** simulates all executions compatible with **M**
  - ▹ Simulates each thread s.t. its local computation is consistent with the memory sequence

Sequentialization of Concurrent Programs

Basic Idea:

> **convert concurrent programs into *equivalent* sequential programs**

Mu-CSeq Approach:

$$Pc \rightsquigarrow M : Ps$$

- **M** is a guessed sequence of write operations into the shared memory
- **Ps** simulates all executions compatible with **M**
  - Simulates each thread s.t. its local computation is consistent with the memory sequence

Our analysis is bounded on the number of memory write operations

Memory Unwinding

“memory”

x	y	...	z
0	0	...	0

Memory Unwinding

"memory"

pos	x	y	...	z
0	0	0	...	0
1	4	0	...	0
2	4	2	...	0
3	4	3	...	0
4	4	3	...	42
...	...	...	...	...
N	0	3	...	42

Guess and store sequence of individual write operations:

- add *N* copies of shared variables ("memory")
  `_memory[i,v]` is value of *v*-th variable after *i*-th write

Memory Unwinding

	"memory"				"writes"	
pos	x	y	…	z	thr	var
0	0	0	…	0	-	-
1	4	0	…	0	1	x
2	4	2	…	0	1	y
3	4	3	…	0	2	y
4	4	3	…	42	1	z
…	…	…	…	…	…	…
N	0	3	…	42	2	x

Guess and store sequence of individual write operations:

- add *N* copies of shared variables ("*memory*")
  `_memory[i,v]` is value of *v*-th variable after *i*-th write
- add array to record writes ("*writes*")
  i-th write is by `_thr[i]`, which has written to `_var[i]`

Simulation

Basic Idea:

simulate all executions compatible with guessed memory unwinding

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- uses auxiliary variables
  - `thread` (id of currently simulated thread)
  - `pos` (current index into unwound memory)

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- every thread is translated into a function
  - simulation starts from main thread

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- uses auxiliary variables
  - `thread` (id of currently simulated thread)
  - `pos` (current index into unwound memory)

- every thread is translated into a function
  - simulation starts from main thread

- each **thread creation** is translated into a function call

Simulation

Basic Idea:

simulate all executions compatible with guessed memory unwinding

- every read / write is translated into a function call

Simulating reads and writes

Basic Idea:

simulate all executions compatible with guessed memory unwinding

- every read / write is translated into a function call

```
void write(uint var_name, int val)
  pos=next_write(pos,thread);
  assume(_var[pos]== var_name
   && memory[pos, var_name]==val);
}
```

	"memory"				"writes"	
pos	x	y	...	z	thr	var
0	0	0	...	0	-	-
1	4	0	...	0	1	x
2	4	2	...	0	1	y
3	4	3	...	0	2	y
4	4	3	...	42	1	z
...	...	...	...	...	...	...
N	0	3	...	42	2	x

Simulating reads and writes

Basic Idea:

> **simulate all executions compatible with guessed memory unwinding**

- every read / write is translated into a function call

```
int read(uint var_name) {
  uint jmp=*;
  assume(jmp>=pos
   && jmp<next_write(pos,thread);
  pos=jmp;
  return _memory[pos, var_name];
}
```

"memory"

pos	x	y	...	z
0	0	0	...	0
1	4	0	...	0
2	4	2	...	0
3	4	3	...	0
4	4	3	...	42
...	...	...	...	...
N	0	3	...	42

"writes"

thr	var
-	-
1	x
1	y
2	y
1	z
...	...
2	x

Improvements

- Explicit representation of the memory

"memory"

pos	x	y	...	z
0	0	0	...	0
1	4	0	...	0
2	4	2	...	0
3	4	3	...	0
4	4	3	...	42
...	...	...	...	...
N	0	3	...	42

"writes"

thr	var
0	0
1	x
1	y
2	y
1	z
...	...
2	x

- Read and Write can be simulated using a constant number of steps

- *"memory"* size depends on the number of shared variables

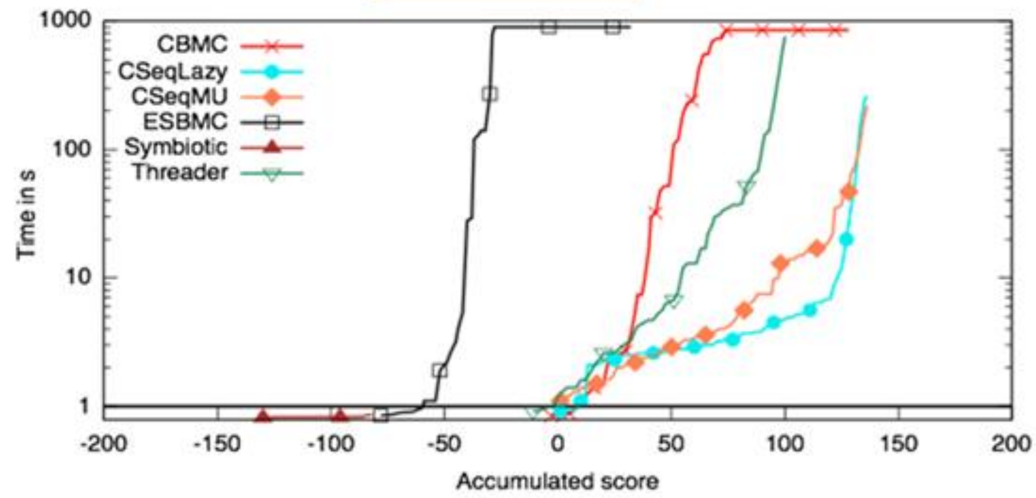
Evaluation
and
Future Work

Evaluation: SV-COMP2014

Lazy-CSeq won the **Gold Medal** and
MU-CSeq won the **Silver Medal**
in the Concurrency category

- 76 concurrent C programs
  - ▹ **UNSAFE** instances: 20 programs containing a bug
  - ▹ **SAFE** instances: all the others
- 4,500 l.o.c.

1) Lazy-Cseq: 1,000s, 136pts
2) MU-Cseq: 1,200s, 136pts
3) CBMC: 29,000s, 128pts



Results:

- small analysis times
- no missed bugs!

Future Work

- concurrency models
  POSIX threads model *Shared-Memory* concurrency,
  we plan to add support *Message Passing* (MP) programs

- memory models
  so far we assumed *Sequential Consistency* (SC),
  we plan to extend to *Weak Memory Models* (WMM)
  used in modern computer architectures

- backend support
  we have achieved fast bug-hunting with bounded model-checkers,
  we have started some preliminary work to support abstraction-based backends as well.

Thank You

users.ecs.soton.ac.uk/gp4/cseq