PReach: A real-world, parallel program in Erlang

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Outline

Terminology *(Stolen from wikipedia)*

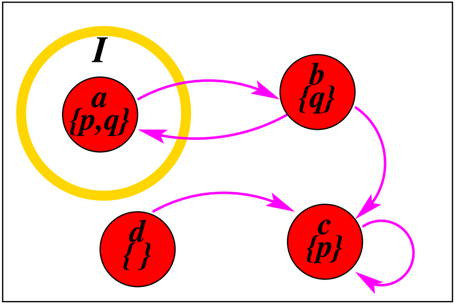
Kripke Structure ("system"): A 4-tuple (S, I, R, L) where

- S is a (finite) set of states,
- $I \subseteq S$ are the initial states,
- $R \subseteq S \times S$ is the transition relation,
- $L : S \to 2^{AP}$ is the labelling function – where AP is a set of atomic propositions (boolean variables)

Reachable states: The set of all states $s \in S$ for which there is a path from some $s_{init} \in I$ through R to s

Example: *(also stolen from wikipedia)*

- $AP = \{p, q\}$
- $S = \{a, b, c, d\}$
- $I = \{a\}$
- $R = \{(a, b), (b, a), (b, c), (c, c), (d, c)\}$
- $L = \{(a, \{p, q\}), (b, \{q\}), (c, \{p\}), (d, \{\})\}$
- $Reachable = \{a, b, c\}$
- $Bad \equiv \neg p \wedge \neg q$



More Terminology

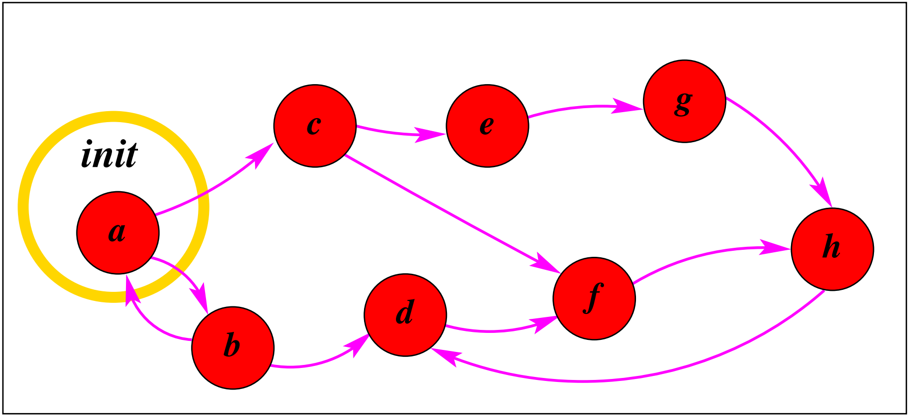
- Model Checking (MC): An automatic technique for checking if a system adheres to a specification, given by a formula expressed in some logic (e.g. CTL, LTL, CTL*, etc)
  - The simplest specification is safety, i.e. "is there a reachable *Bad* state?"
  - *Bad* is a predicate over *AP*
- Explicit-State Model Checking: A model checking algorithm that represents each reachable state distinctly in memory
  - A brute-force approach to MC
  - Alternative to explicit-state MC is symbolic MC, where sets of states are represented by a formula over *AP*, (i.e., BDDs, Interpolants, IC3).

Murφ

- A language for describing hardware systems and an associated explicit-state model checker (for safety properties)
- Murφ system has 4 parts:
  1. variables (think booleans or enumerated types, describing AP),
  2. initial states (a predicate over the variables describing I),
  3. guarded commands (of the form $g \Rightarrow a$, where g is a "guard" and a is an update action, describing R).
  4. invariants (a predicate for *Bad* states).
- Model checking a Murφ system has 3 possible outcomes: pass, fail with counter example, or run out of memory

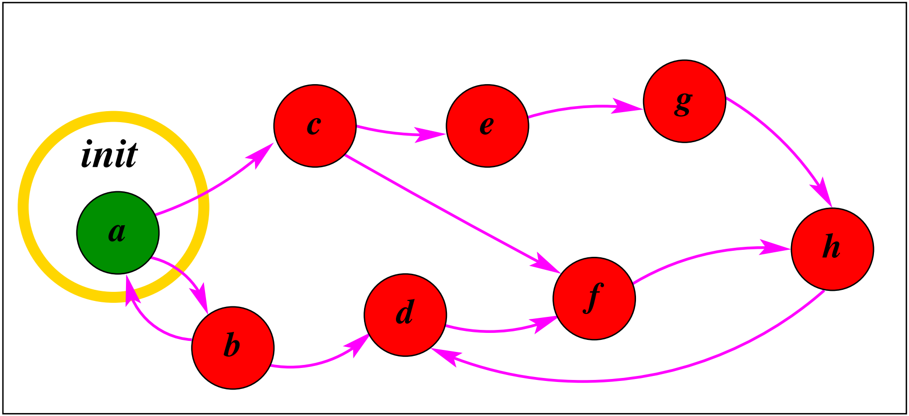
Explicit-state MC by BFS

- Set of visited states **V** $= \emptyset$
- Queue of expanded states **WQ** $= []$



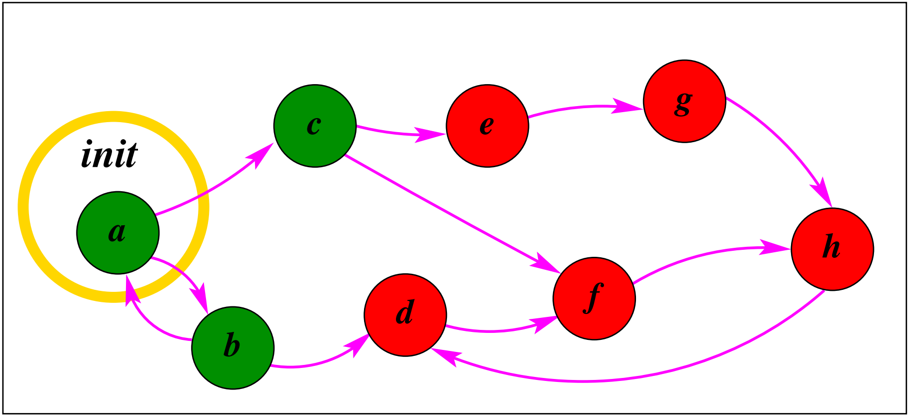
Explicit-state MC by BFS

- Set of visited states **V** $= \{a\}$
- Queue of expanded states **WQ** $= [a]$



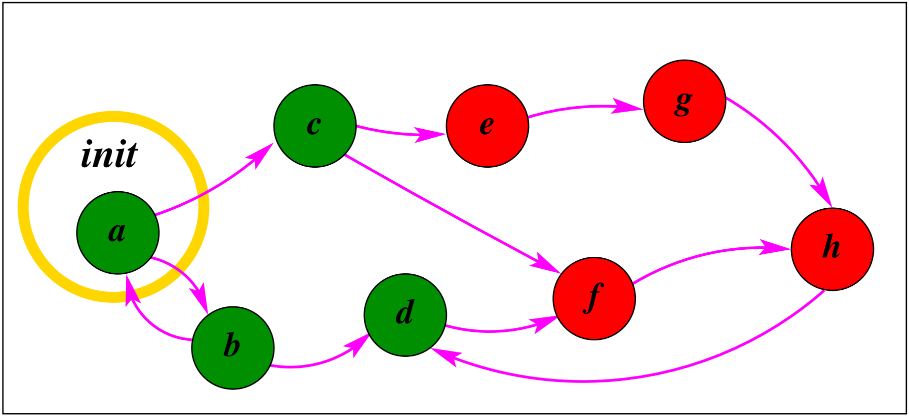
Explicit-state MC by BFS

- Set of visited states **V** $= \{a, b, c\}$
- Queue of expanded states **WQ** $= [b, c]$



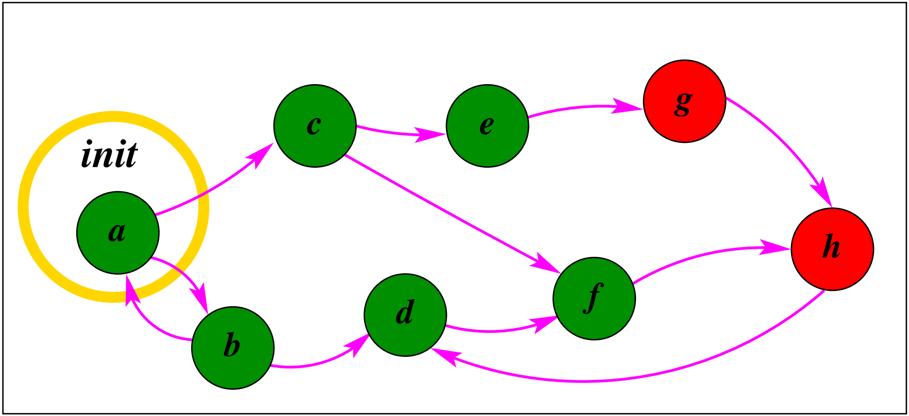
Explicit-state MC by BFS

- Set of visited states **V** $= \{a, b, c, d\}$
- Queue of expanded states **WQ** $= [c, d]$



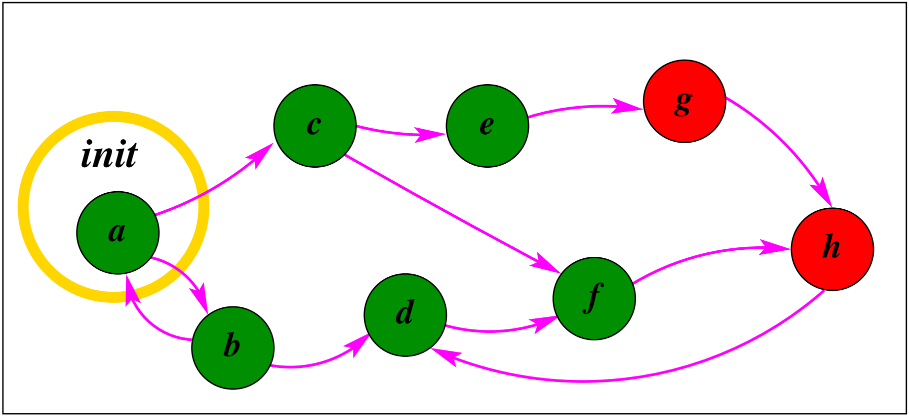
Explicit-state MC by BFS

- Set of visited states **V** $= \{a, b, c, d, e, f\}$
- Queue of expanded states **WQ** $= [d, e, f]$



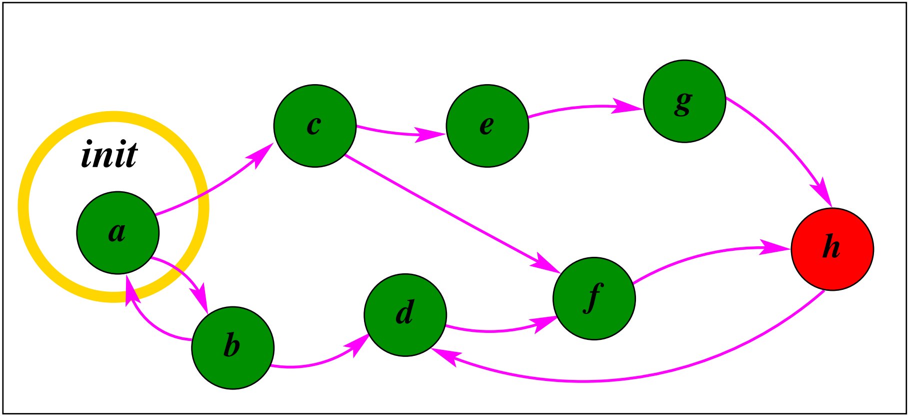
Explicit-state MC by BFS

- Set of visited states **V** $= \{a, b, c, d, e, f\}$
- Queue of expanded states **WQ** $= [e, f]$



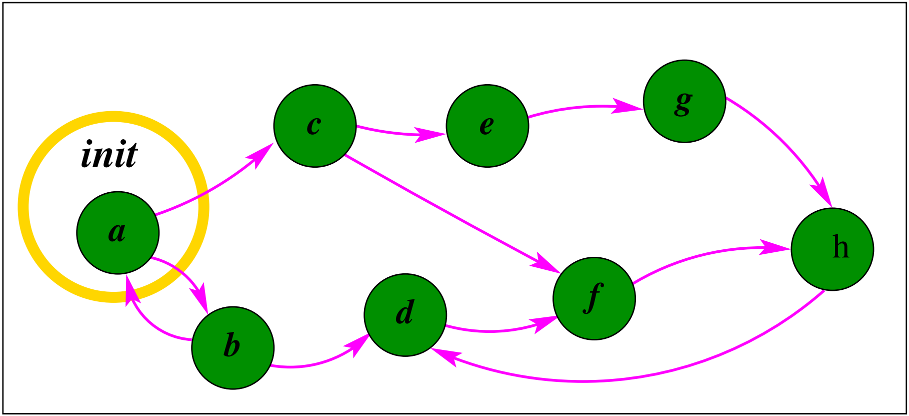
Explicit-state MC by BFS

- Set of visited states **V** $= \{a, b, c, d, e, f, g\}$
- Queue of expanded states **WQ** $= [f, g]$



Explicit-state MC by BFS

- Set of visited states **V** $= \{a, b, c, d, e, f, g, h\}$
- Queue of expanded states **WQ** $= [g, h]$



Explicit-state MC by BFS

- Set of visited states **V** $= \{a, b, c, d, e, f, g, h\}$
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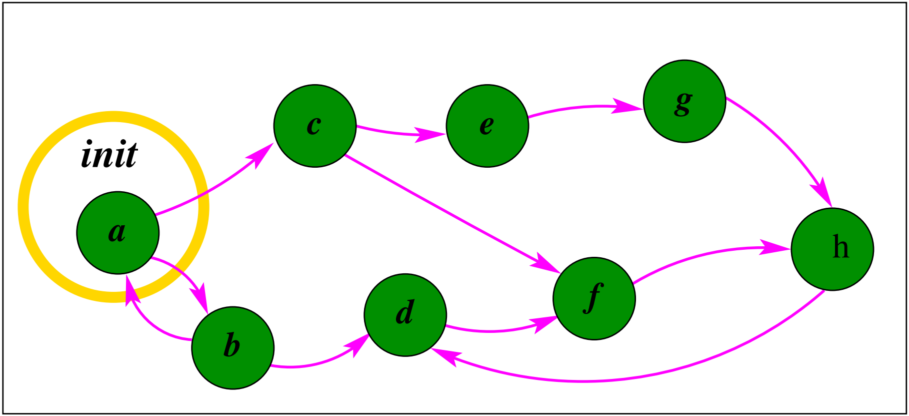

Explicit-state MC by BFS

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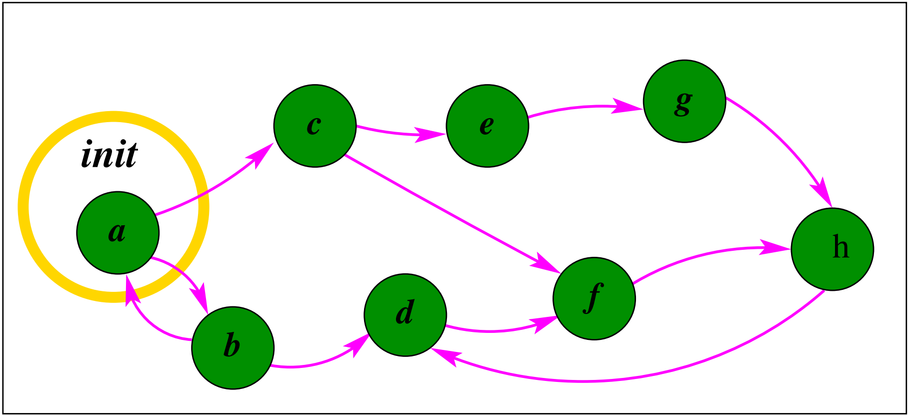


State-space explosion

- Bad news: *The number of reachable states tends to blow up exponentially in the number of variables, i.e* $|Reachable| \propto 2^{|AP|}$.
- In other words, adding just one more boolean variable to the system can cause the number of states to DOUBLE! This means double the memory and double the runtime for explicit-state MC of safety.
- ALL methods of MC suffer from this problem.
- Methods to curb: abstraction, symmetry reduction, partial order reduction
- Another method: distribute the MC computation among a network of machines!

Why Distributed Explicit State Model Checking?

- State-space explosion assures us that we can always use more memory (and cycles)
- Easily takes advantage of the aggregate memory of commodity machines and multiple cores

Question: Who cares about increasing our MC capabilities by a factor of $[100, 1000]$ when we face an exponential explosion?

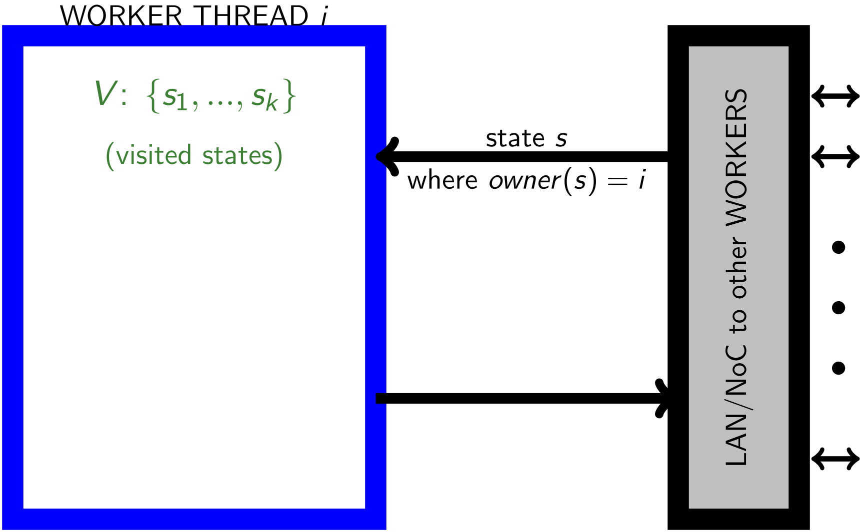
1. This factor can make the difference between verifying a very high level model and one that includes critical details
2. Techniques of abstraction/decomposition require human effort – terminate the human task sooner and hand it off to a large cluster

Outline

Stern-Dill Algorithm[SD97] Overview

- Simple and fundamental approach to distributing explicit-state model checking (for safety)
  - Assumes a uniform random hash function $owner : States \rightarrow PIDs$
  - Thread PID i only stores states s such that $owner(s) = i$.
- Each PID maintains two data structures:
  - **V**: Set of (owned) states visited so far
  - **WQ**: List of states waiting to be expanded
- Start: compute initial states and send to their owners
- Iterate: state sucessors are sent to their respective owners
- Termination: when each **WQ** is empty and no messages are in flight

Stern-Dill Pseudocode



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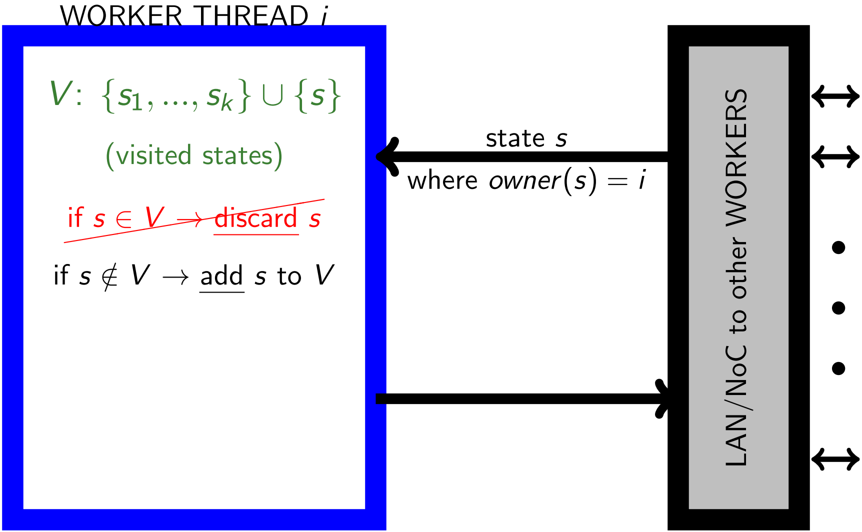

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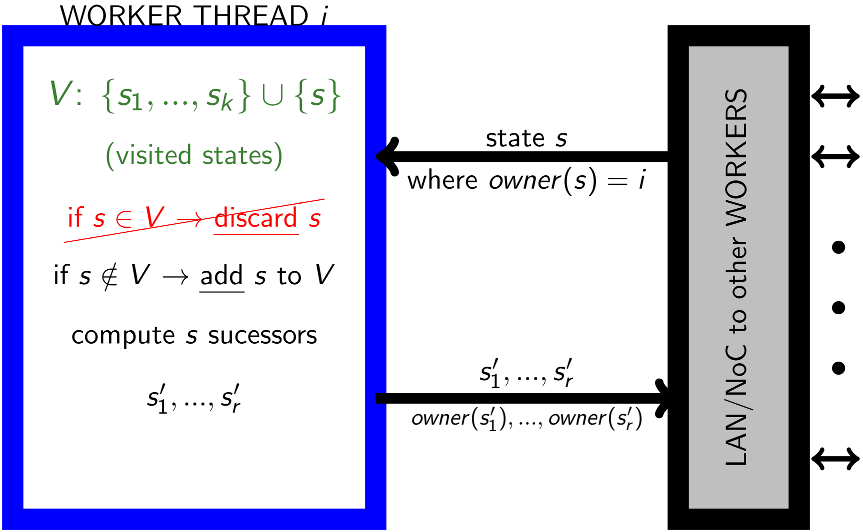


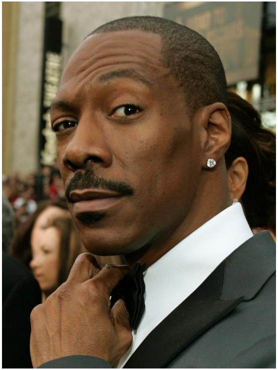
Some Optimizations

- "State Batching": from [SD97], delay sending states to another thread until enough states accumulate
  - Mitigates the overhead of network message passing
  - Important: appropriate proviso to avoid deadlock, i.e. always send states eventually
  - Every DEMC tool does this in some form
- "Less-Uniform Partitioning": from parallel Spin [LS99]
  - States are composed of sets of variables $(s_1, s_2, ..., s_k)$ for k Promella processes
  - Instead of *owner* depending on each s_i, let *owner* depend on only one s_i
  - If most transitions don't change s_i's variables, state sucessors stay local to the thread (no communication necessary)
  - However: may be less balanced than *owner* depending on all variables

Eddy (Murφ)[MPS+09]

Parallel implementation of the Murφ model checker, from Univ. of Utah

- Use MPI for distributed communication, split one Stern-Dill thread into two p-threads
- For each peer: maintain a communication queue of 8 batches of 1024 states
- Computation thread: expands states and writes to comm. queues
- Communication thread: wakes up when a message arrives or a batch fills up
- Overlaps message handling with state expansion; good from a software engineering perspective



Outline

What is PReach[BBdP+10]?

- PReach (*P*arallel *REACH*ability) is a distributed explicit-state model checker (UBC and Intel)
- Input: the Murφ modeling language; checks state invariants
  - New: Murφ syntax extended by PReach to support deadlock freedom and transition invariants
- Runs on a network of heterogenous machines including multicore
- Communication is handled by *Erlang*, a distributed functional language, while C++ libraries handle compute-intensive model checking tasks
- Emphasis on scalability – billions of states
  - Robustness
  - Simplicity
  - Performance? (a secondary concern)

Stern-Dill in PReach

WQ: list of states; stored on disk
V: set of states; Murφ hash table in memory

```
while ¬TERMINATED() {
    if ¬EMPTY(WQ) {
        s := DEQUEUE(WQ);
        foreach r in SUCCESSORS(s) {
            OWNER(r) ! r;   }}     # send successor state r
    if RECEIVE(s) {
        if ¬IS_MEMBER(s, V) {
            ADD_ELEMENT(s, V);
            CHECK_INVARIANTS(s);
            ENQUEUE(s, WQ);
}}}
```

Distributed Termination

How can we be sure that each **WQ** is empty and no messages are in flight?

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1. Each thread keeps two counters, *NumSent* and *NumRecd*
   - *NumSent*++ when sending a state; *NumRecd*++ when a state is received

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3. When root receives im_idle, broadcast request_stats to all workers

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2. When my **WQ** has been empty for some threshold amount of time, send message im_idle to root
3. When root receives im_idle, broadcast request_stats to all workers
4. When a worker receives request_stats, HALT computation and report:
   - If my **WQ** is nonempty: send im_not_done to root
   - If my **WQ** is empty: send {my_stats, *NumSent*, *NumRecd*} to the root

Distributed Termination

How can we be sure that each **WQ** is empty and no messages are in flight?

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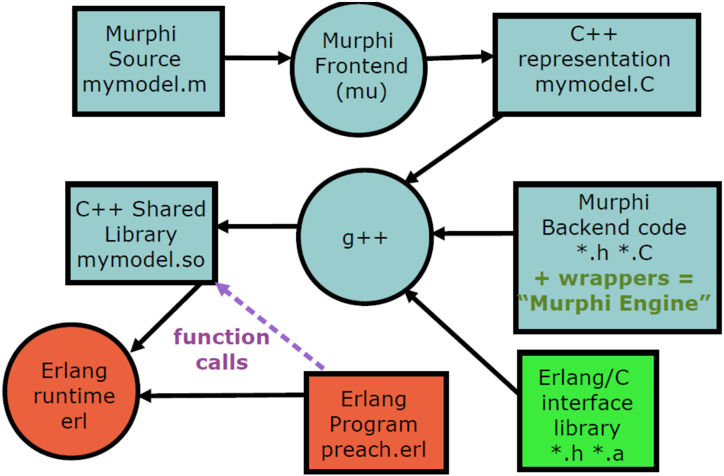
   - If my **WQ** is empty: send {my_stats, *NumSent*, *NumRecd*} to the root
5. Root decides if we're really done:
   - If root receives my_stats messages from all workers AND $\sum NumSent_i = \sum NumRecd_i$, broadcast terminated
   - Otherwise: broadcast resume message

Architecture

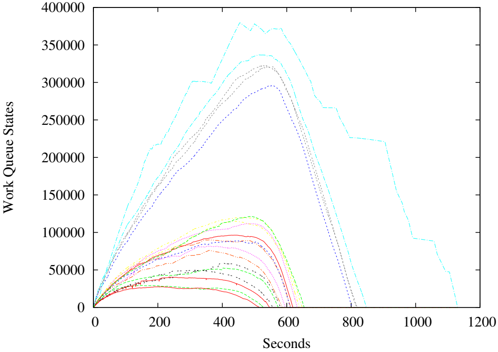
Murφ + tweaks + Erlang = PReach



Load Balancing

Bad News: While state space is partitioned evenly, dynamic load (**WQ** length) can vary a lot

- Some threads will finish early and idle
- Heterogenous computing environment exacerbates the problem



Good News: We can effectively balance load **without** altering the static state space partition

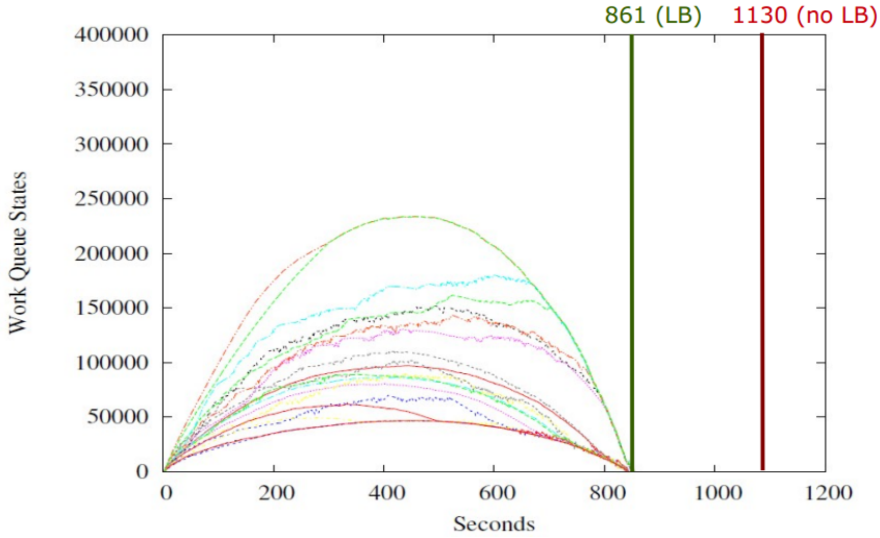
Stern-Dill in PREACH

WQ: list of states;
V: set of states;

```
while ¬TERMINATED() {
    if ¬EMPTY(WQ) {
        s := DEQUEUE(WQ);
        foreach r in SUCCESSORS(s) {
            OWNER(r) ! r;    }}
    if RECEIVE(s) {
        if ¬IS_MEMBER(s, V) {
            ADD_ELEMENT(s, V);
            CHECK_INVARIANTS(s);
            ENQUEUE(s, WQ);
}}}
```

Insight: After *s* is added to **V**, it doesn't matter which thread computes the sucessors of *s*!

Load Balancing Enabled



Results and Status

The "BIG Model": Intel industrial cache coherence protocol.

- $\approx$ 95 billion states! ☺
- $\approx$ 10 days runtime on 120 cores
- $\approx 110,000$ states/second; $\approx$ 900 states/second/core

Status:

- Currently in use at Intel
- Used by computer architects at Duke University, and a handful of other people at various institutions
- Available for download [BEBdP11]

Outline

0. Background: Explicit-State Model Checking
1. Stern-Dill Algorithm: Distributed BFS
   - + Other Tools
2. The PReach Model Checker
3. Remarks
4. Erlang Tips + Tricks

Erlang Pros + Cons

Was Erlang a good choice to build an industrial, explicit-state model checker?

Short answer is YES:

- Erlang is easier to program than C/C++ with MPI – original PReach prototype written in one weekend
- A good choice for this project where parallel speedup is not paramount, rather stability and scalability
- Small codebase, $\approx$ 1000 lines.
- I agree with these statements from `erlang.org/faq/how_do_i.html`:
  - Lines of code: "A reasonably complex problem involving distribution and fault tolerence will be roughly five times shorter in Erlang than in C"
  - Performance: Number crunching is about 10 times slower in Erlang than C; communication heavy programs are about the same speed.

Erlang Pros + Cons

Was Erlang a good choice to build an industrial, explicit-state model checker?

Short answer is YES, **however...**

- Documentation for Erlang isn't great, and some of the more obscure features aren't explained well
- The method of interfacing with C code (.so files) is miserable, and the API seems to change with new Erlang versions ☹
  - We learned how to do this from some random blog
  - PReach uses $\approx$ 30 interface functions that call into Murφ C code, took some trial and error to learn how to pass various data types

A Few Directions

1. Bottlenecks: in PReach (+ other tools), the bottleneck is state-expansion – especially bad in industrial models with ≈ 5000 guarded commands!
   - Several studies have considered GPU-accelerated model checking;
   - Recent work [BBBC10] is the first (that I've seen) to use more than one GPU – although they only use 2, achieving a factor of 5 speedup
2. Crash Recovery: an important consideration when running hundreds of machines for days
   1. Snapshot **V** and **WQ** periodically: can recover from model checking thread crashes
   2. Duplicate state ownership: can recover from a machine going down
3. PReach has a modest number of parameters for load balancing, batching, flow control
   - Use machine learning techniques [HHLBS09] to tune parameters according to a new hardware configuration!

Outline

Profiling

- There's 4 profiling tools in Erlang: fprof, eprof, cover, cprof
- My preference is eprof
- Easy to use:
  - At the start of your program, insert the lines
    ```
    eprof:start(),
    eprof:start_profiling([self()]),
    ```
  - At the end of your program, inser the lines
    ```
    eprof:stop_profiling(),
    io:format("Here's the eprof output:~n"),
    eprof:analyze(),
    ```
- Gives the number of times each function was called as well as the total time spent in each function
- Program slowdown is modest

The Process Dictionary

For when you REALLY want global variables...

- Each process has it's own "dictionary" that can be used to store global variables
- Set and get with `put(Key,Value)` and `get(Key)`; delete with `delete(Key)`
- Really useful for debugging or gathering program statistics

Case vs. If

I slowly learned to always use case, and never use if

- Suppose we want to implement a set with a list (i.e. only insert elements that are new).
- With case:
```
insert(X,Set) ->
case lists:member(X,Set) of true -> Set;
false -> [X | Set] end.
```
- With if:
```
insert(X,Set) ->
IsInSet = lists:member(X,Set),
if IsInSet -> Set;
true -> [X | Set] end.
```

Beware Big Mailboxes

Warning: The time it takes to receive a message is proportional to the number of messages waiting in the inbox!

- Ignoring this issue in PReach causes crashes that arise from some workers slowing down to a halt
- As soon as one worker falls a little behind, it will never catch up because it takes longer to receive states than the others
- Solved with a crediting mechanism
- Lesson: make sure your inboxes don't blow up (say with stale messages)
- Inbox size can be checked with

```
{_, InboxSize} = process_info(self(),message_queue_len)
```

Erlang Pointers

- erlang.org has OK documentation, but I prefer
- Tutorial Blog "Learn you some Erlang for great good!" by Frederic Trottier-Hebert
  learnyousomeerlang.com/content
- Joe Armstrong's Book, "Programming Erlang"
- PReach source
  https://bitbucket.org/jderick/preach

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Thank-you!

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