UNIVERSITÀ DEGLI STUDI DI MILANO
Dept. of Computer Science

Formal Verification Problems in a Bigdata World: Towards a Mighty Synergy

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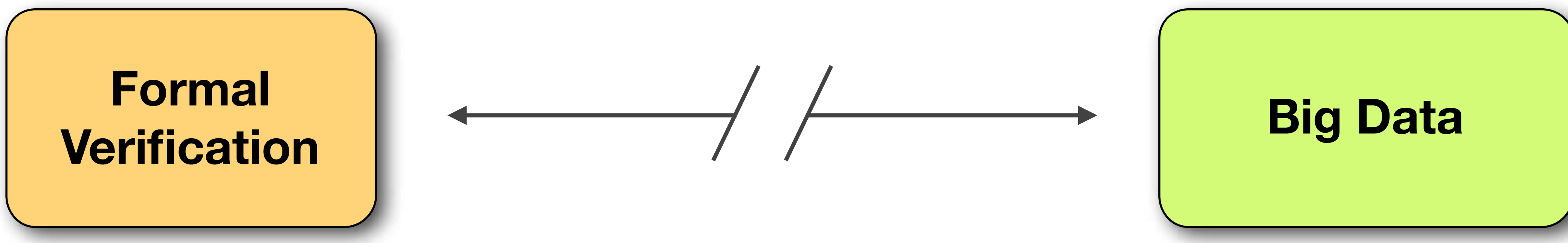
Outline

- Introduction, Motivations, Objectives
- Background
- Some details on:
  - MapReduce
  - Techniques, Frameworks and Tools
- Experiments
- Conclusion
- Planned work

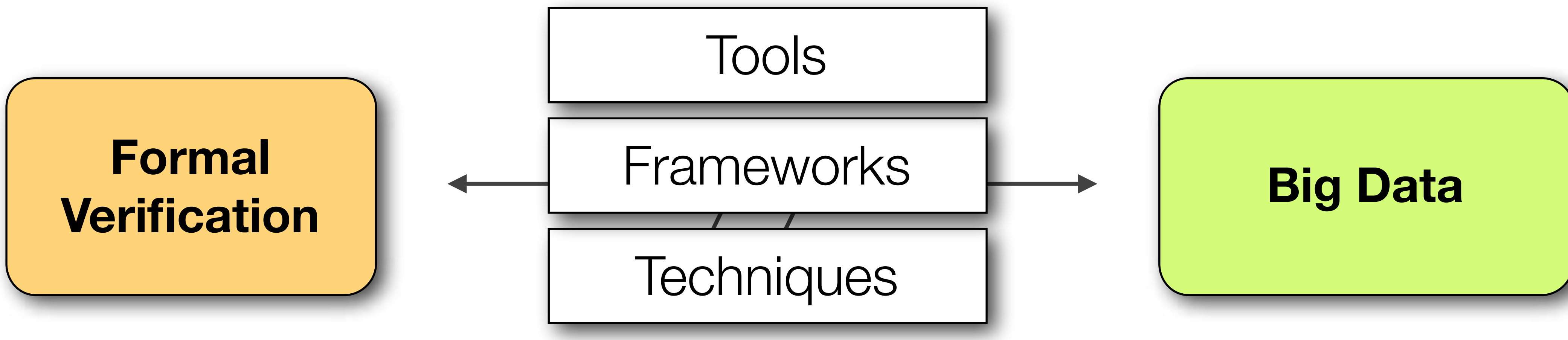
Introduction



- background on formal methods
    - Modeling
    - Interpreting

- deploy techniques into software tools able to analyze large amount of data very reliably and efficiently
- adapting an application for exploiting the scalability provided by cloud computing facilities.

Introduction



- background on formal methods
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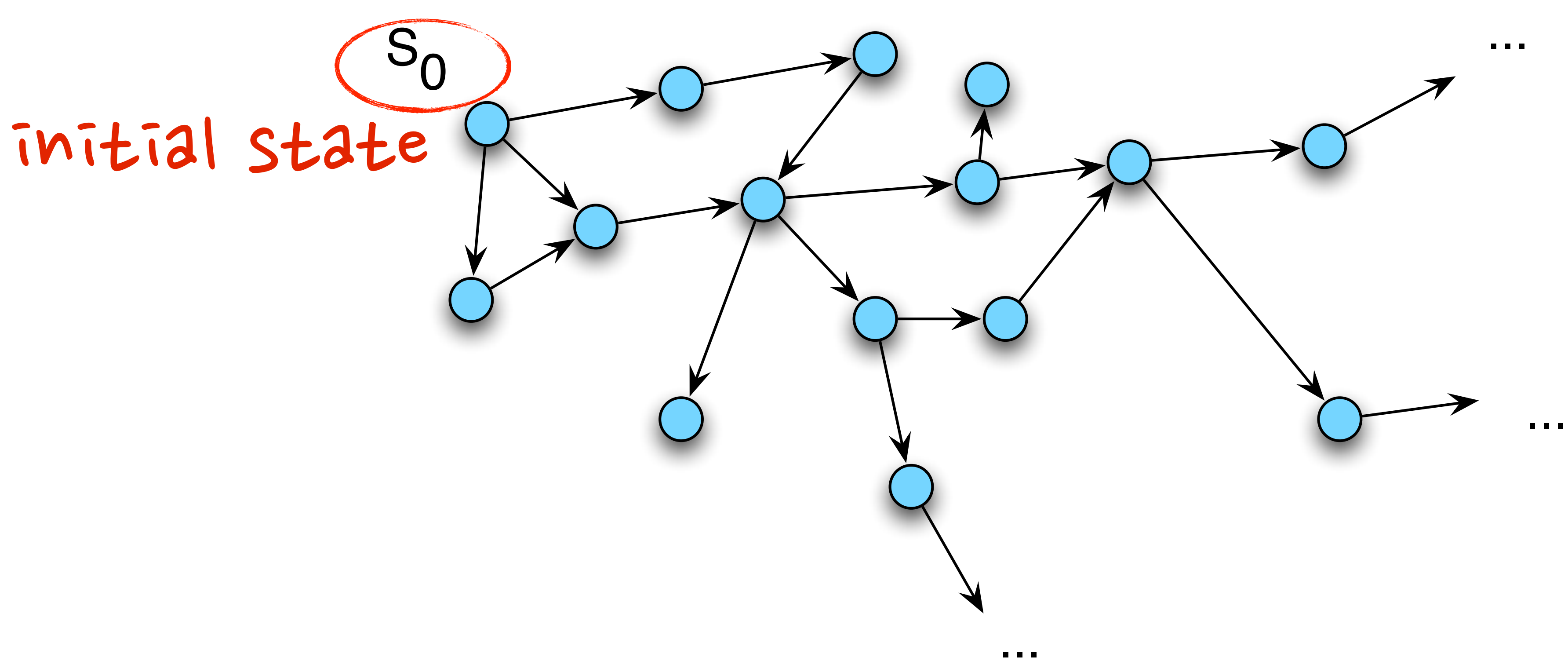
- deploy techniques into software tools able to analyze large amount of data very reliably and efficiently
- adapting an application for exploiting the scalability provided by cloud computing facilities.

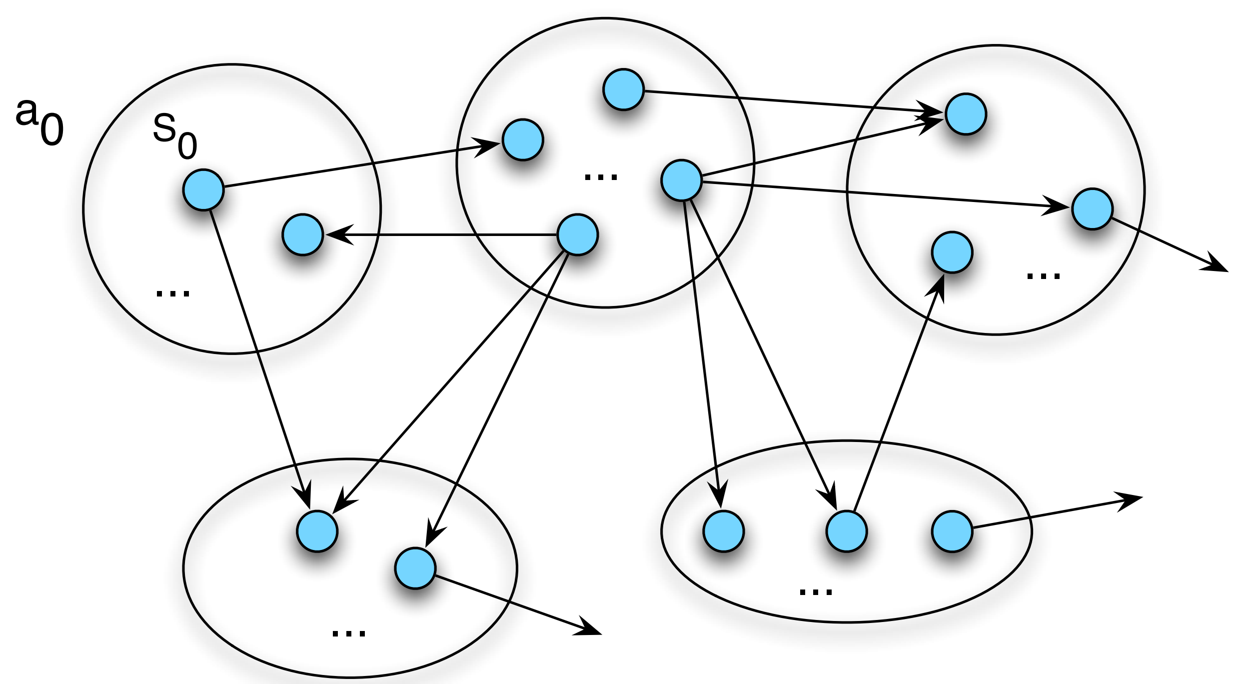
Background

- The behavior of a discrete-event dynamic system is formally given in terms of a labeled state transition system: $(S, \Lambda, \rightarrow)$
- Λ is a set of labels
- $\rightarrow \subseteq S \times \Lambda \times S$ s.t. $(s,\lambda,s') \in \rightarrow$ iff s' reachable from s (written as $s \xrightarrow{\lambda} s'$)



Background

- In general S may be infinite, or even uncountable. Some abstraction techniques are required in order to be able to enumerate the whole state space.
- Abstract State Space: (A, L,⇒)
- Where A is a coverage of S, and $\Rightarrow \subseteq A \times L \times A$ s.t. exists a morphism f which maps Λ labels into L labels.

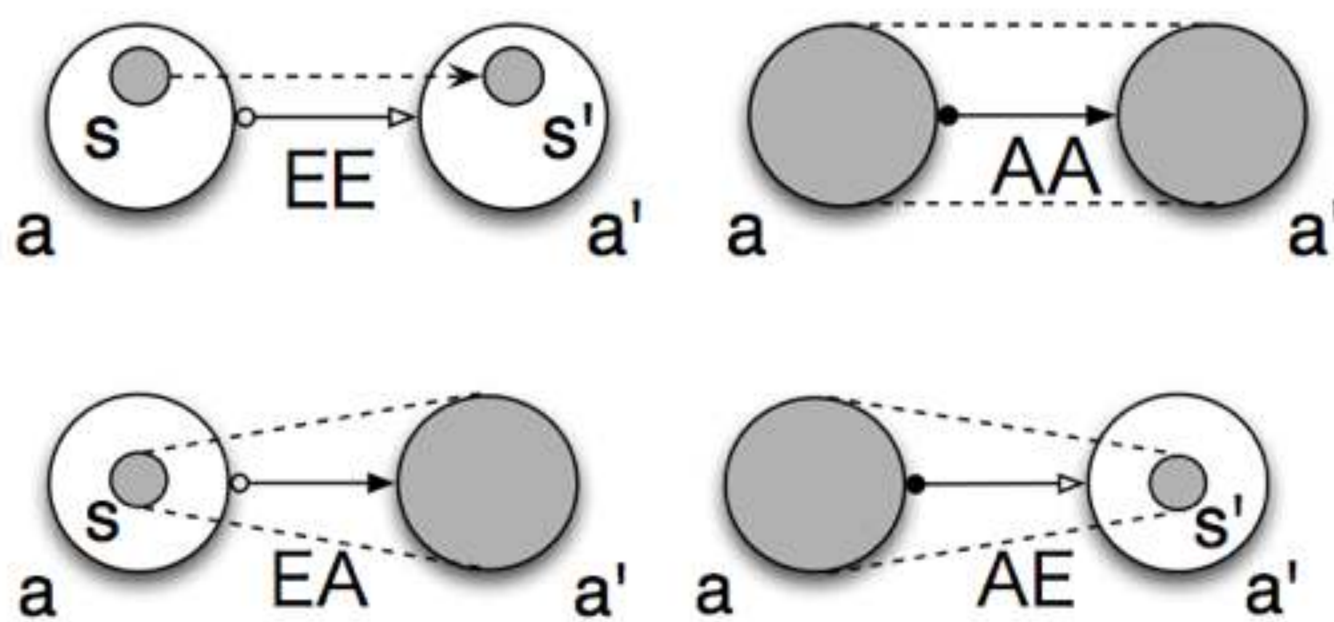


Background

- The relation $\Rightarrow$ satisfies the condition **EE:**

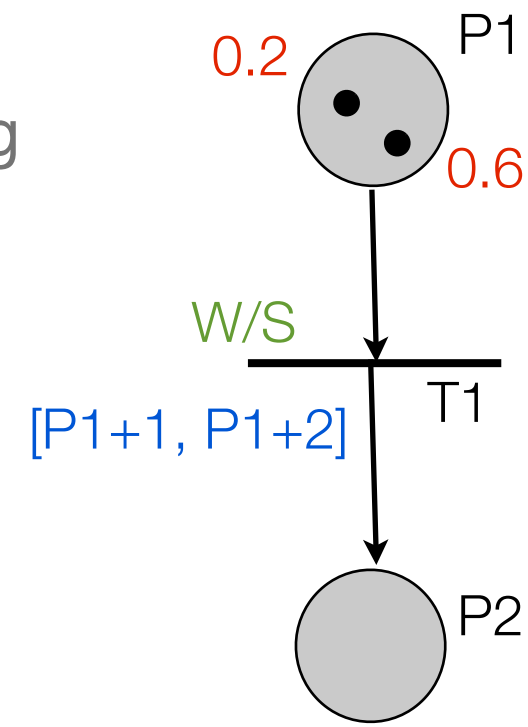
  (1) if $a \overset{l}{\Rightarrow} a'$, then $\exists s \in a,\ s' \in a' : s \overset{\lambda}{\longrightarrow} s'$ with $\lambda \in f^{-1}(l)$

  (2) if $s \overset{\lambda}{\longrightarrow} s'$, then $\forall a \in A$ s.t. $s \in a$, $\exists a' \in A$ s.t. $s' \in a' \wedge a \overset{f(\lambda)}{\Rightarrow} a'$



Time Basic nets - Reachability analysis

- Three key points of the Time Reachability Graph building algorithm allow in many cases the termination.
  - Identification of inclusions between classes of states
  - Erasure of absolute times
  - Identification of anonymous timestamps



Bellettini, C.; Capra, L.; , "Reachability Analysis of Time Basic Petri Nets: A Time Coverage Approach," *Symbolic and Numeric Algorithms for Scientific Computing (SYNASC), 2011 13th International Symposium on* , vol., no., pp.110-117, 26-29 Sept. 2011 doi: 10.1109/SYNASC.2011.16 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6169509&isnumber=6169489

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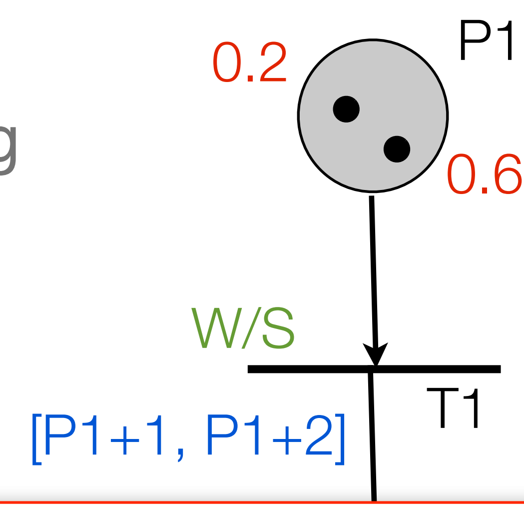

Execution of the Gas Burner example:

Total built abstract states: 22.978

Final abstract state space: 14.563

architecture	# CPUs	tool version	compute model	T	H	f	exec. time
2.4Ghz Intel Core 2 Duo, 2GB RAM	1×2 cores	sequential	local (single machine)	-	-	(2)	~7.5 hrs

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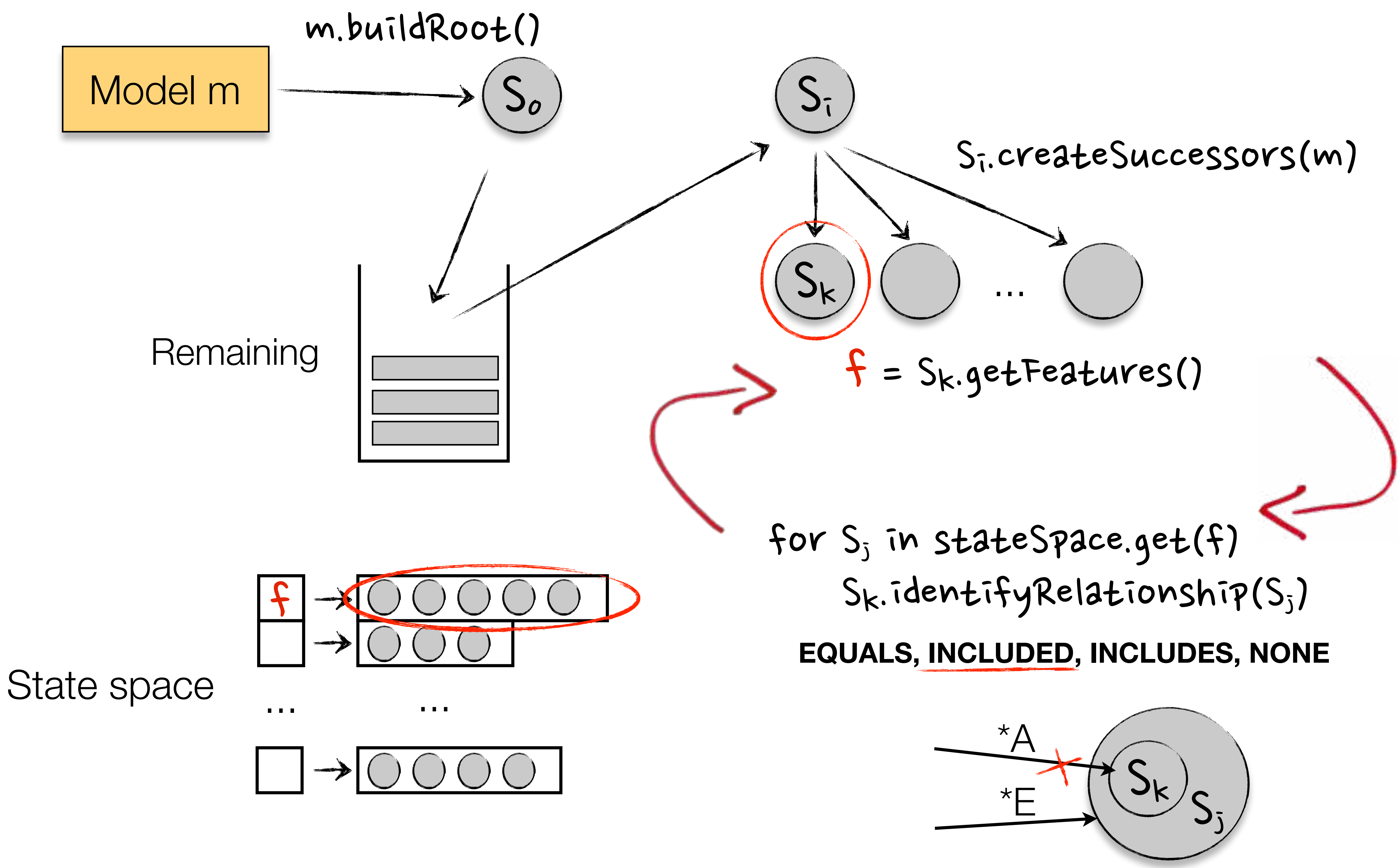
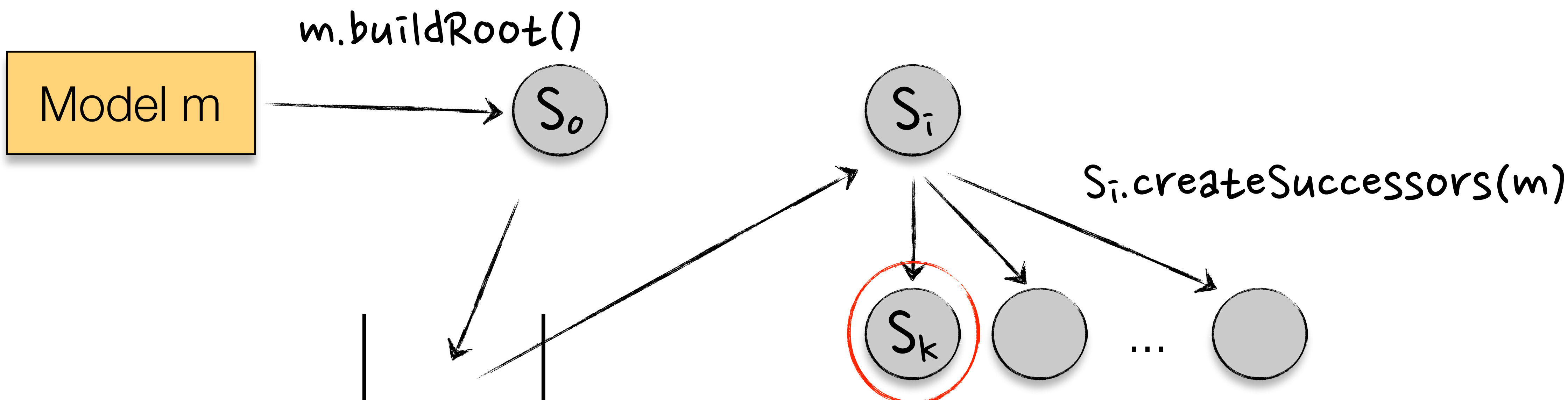
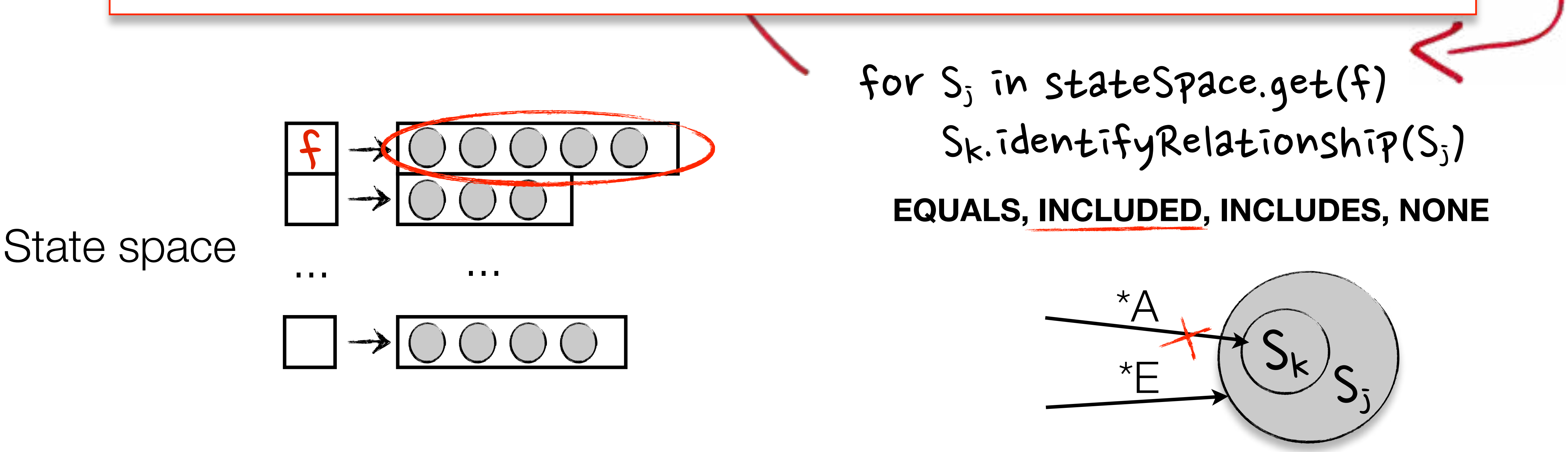
Sequential algorithm



Sequential algorithm

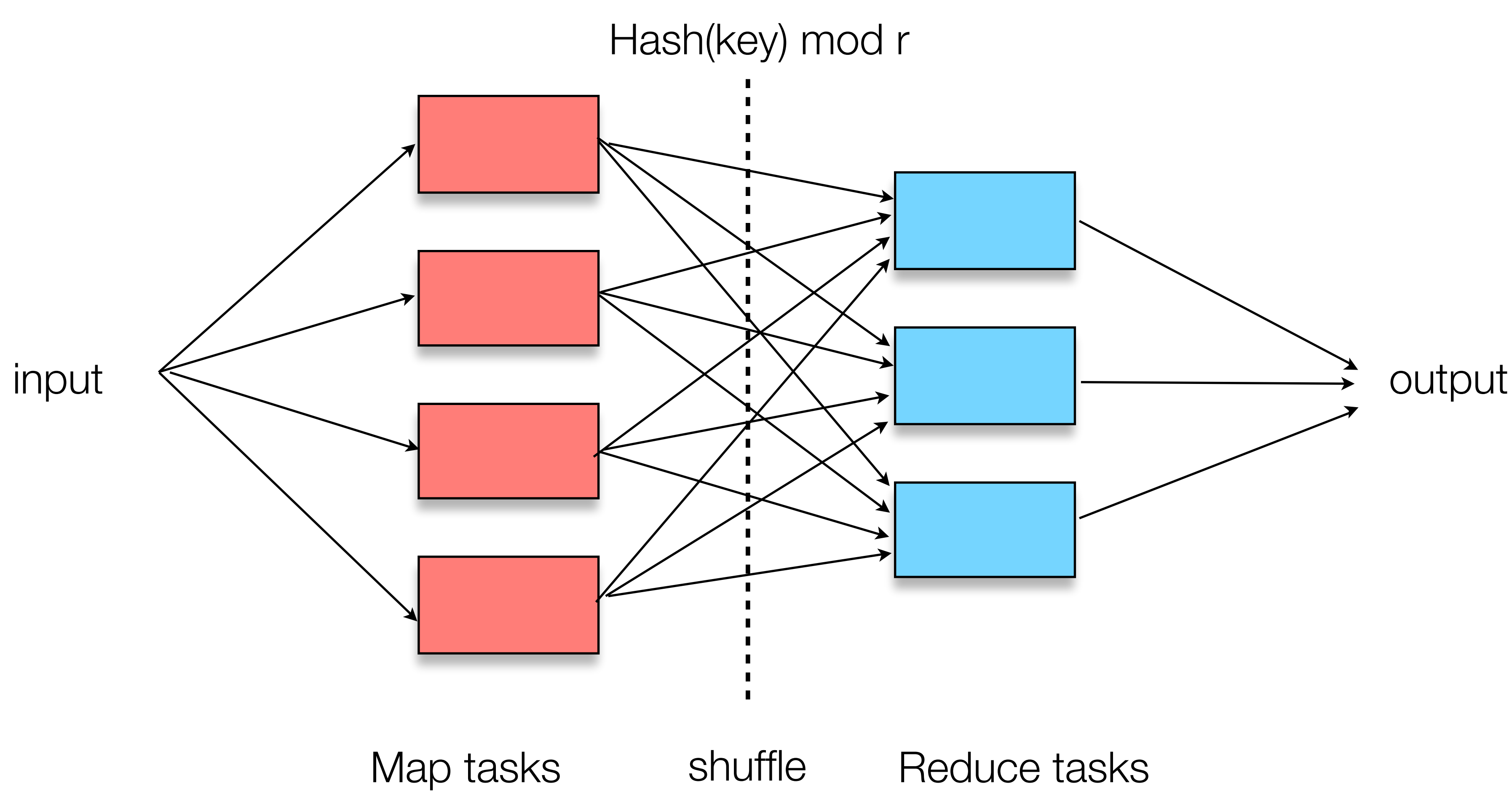


Straightforward, but because of the **state explosion problem** sequential tools may become very slow or even crash.



Map-Reduce

- Map-Reduce job =
  - **Map** function (inputs -> key-value pairs) +
  - **Reduce** function (key and list of values -> outputs)
- Map and Reduce tasks apply Map and Reduce function to many inputs in parallel.

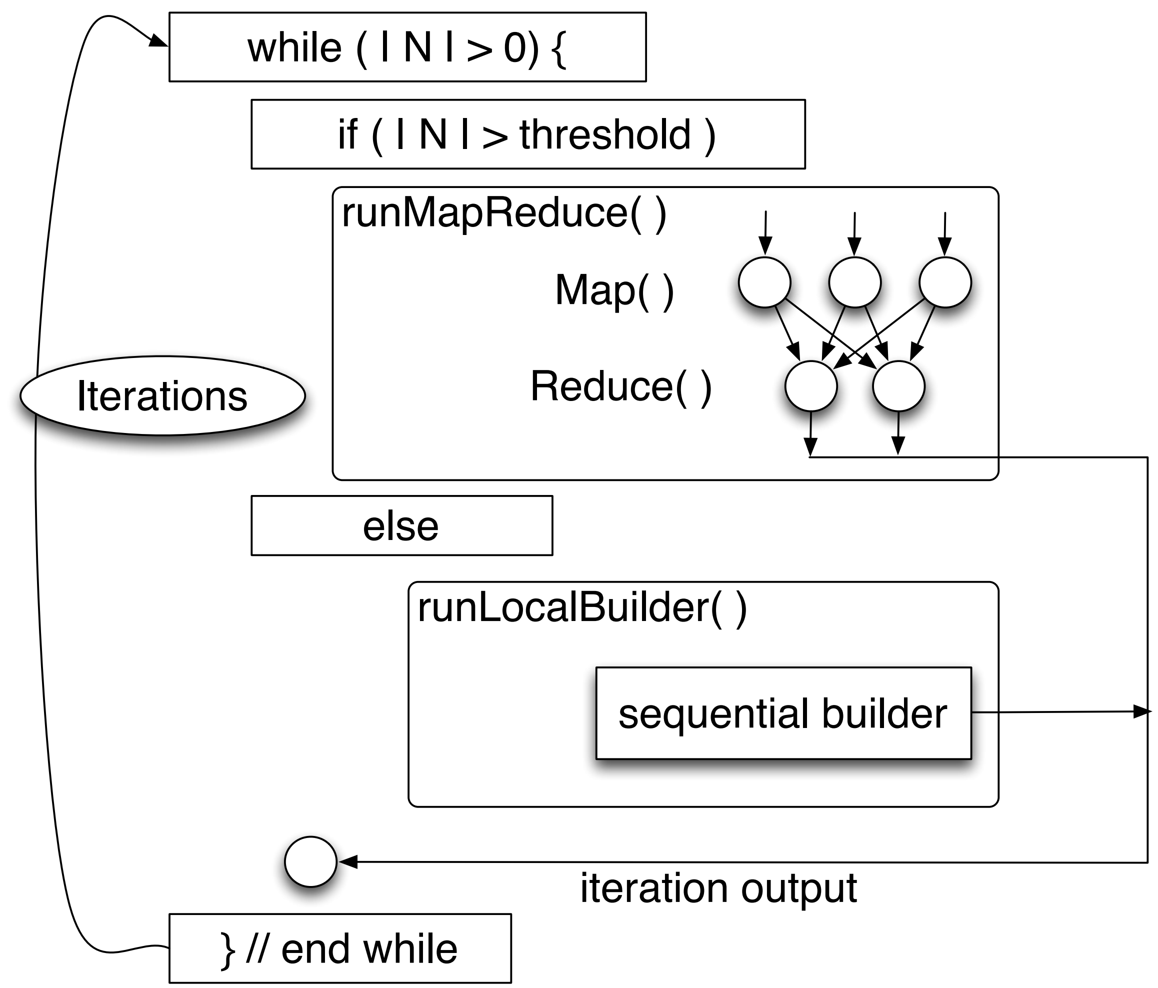


Map-Reduce TB nets analysis tool

- Map step =
  - given an unexplored state, it applies the createSuccessors function. Incoming transitions are stored into destination states by a list of identifiers.
- Shuffle step =
  - Gathers together states potentially related: This is done by using as intermediate keys the evaluation of the getFeatures function.
- Reduce step =
  - given a set of states potentially related, it applies the identifyRelationship function foreach pair of states.
- Building blocks =
  - State = <M,C> pair. M marking, C constraint.
  - identifyRelationship computes the actual relationship between two states according to the following rule: $a \subseteq a' \iff \sigma(M) = \sigma(M') \land C \Rightarrow C'$
  - getFeatures returns just the topological part of $M \equiv \sigma(M)$.

Hybrid Iterative Map-Reduce

- A single Map-Reduce job is not enough: Iterative Map-Reduce
- During the first and last iterations of the algorithm the set of *states* is quite small. Thus a MapReduce job over a large cluster of machines is useless and expensive in term of time and resources.
- The computation starts with a sequential algorithm and goes on until the state space size passes a configurable threshold. After that we distribute the computation over a big cluster.



Hybrid Iterative Map-Reduce

- A single Map-Reduce job is not enough: **Iterative Map-Reduce**
- During the first and last iterations of

Gas Burner example:

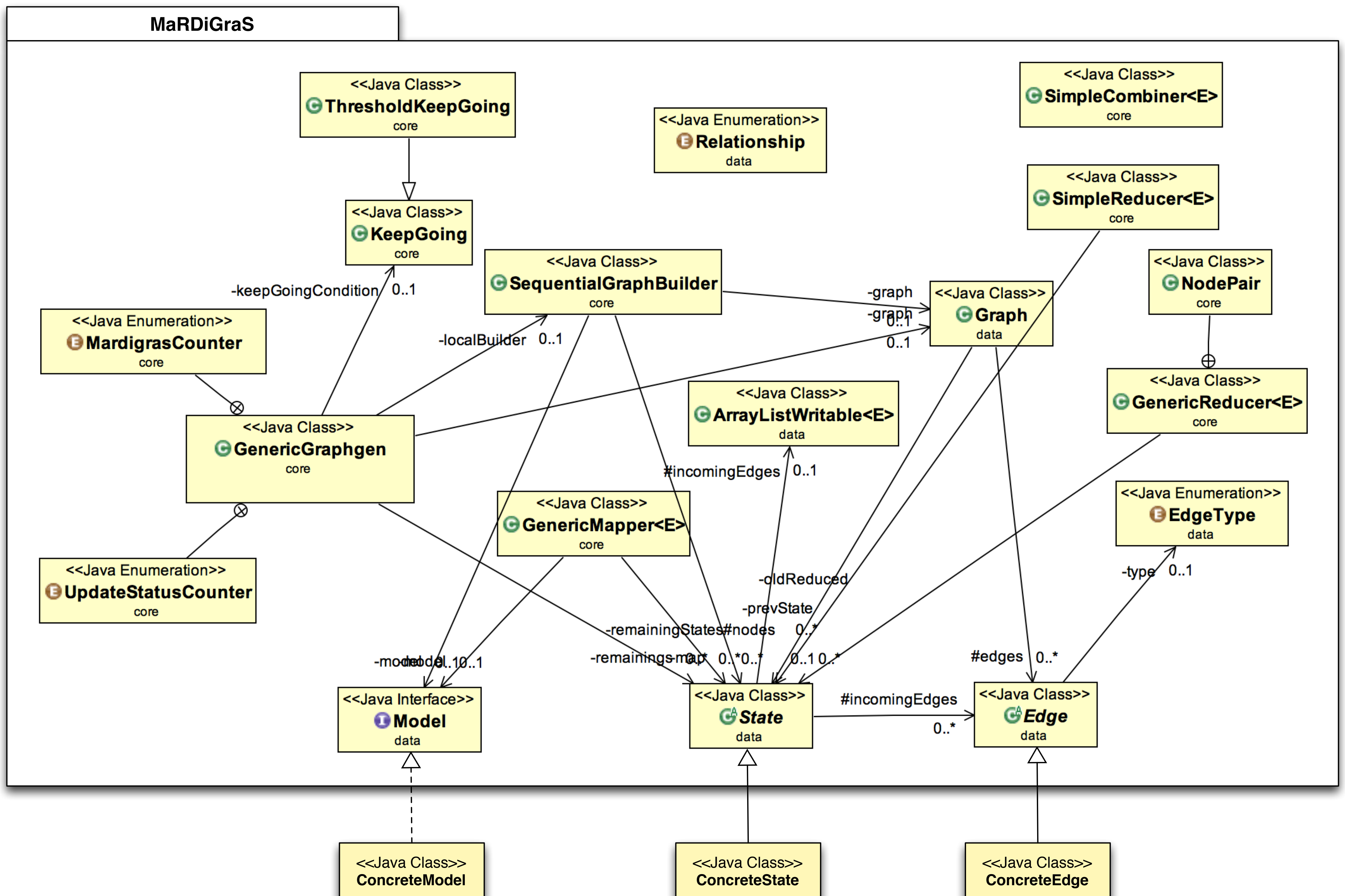
#machines	machine type	#**abstract** states	threshold	time (m)
1	m2.2xlarge	1.456x10	200	175
4	m2.2xlarge	1.456x10	200	95
8	m2.2xlarge	1.456x10	200	39

- The execution with 8 machines is almost 80% faster than the sequential algorithm

we distribute the computation over a big cluster.

MaRDiGraS

MapReduce-based Distributed building of reachability GraphS



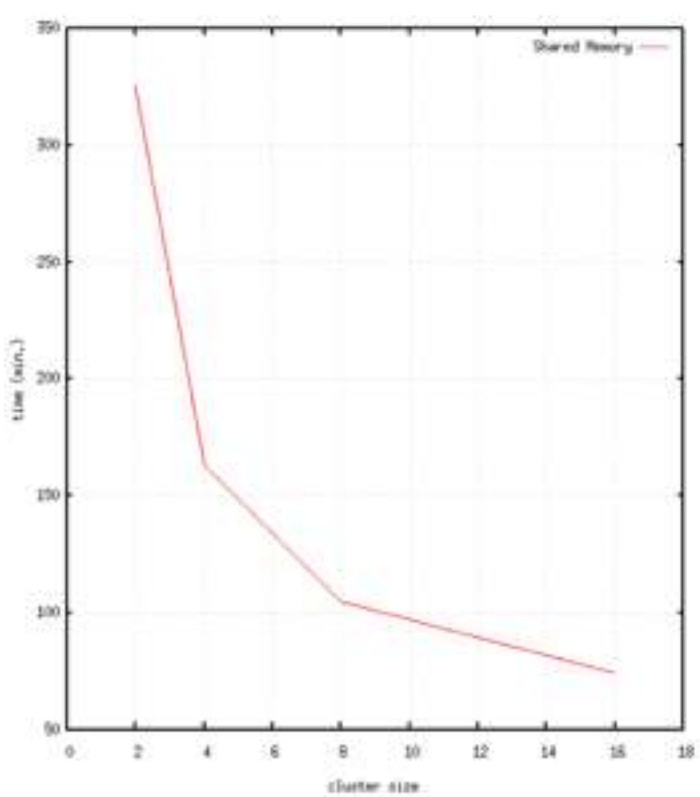
Use Cases

- P/T nets
  - State = <M> marking, associates places with natural numbers.
  - s = s' ⟺ M = M' thus we can use the optimized Reduce phase.
- In order to prove the effectiveness of using MaRDiGraS to improve legacy tools, we adapted an existing P/T nets tool: PIPE.
- To adapt the sequential algorithm of PIPE into a distributed one, we just needed 290 lines of code: a very small number also if compared with the dimension of the effectively used PIPE modules (~6500 lines of code).

Use Cases

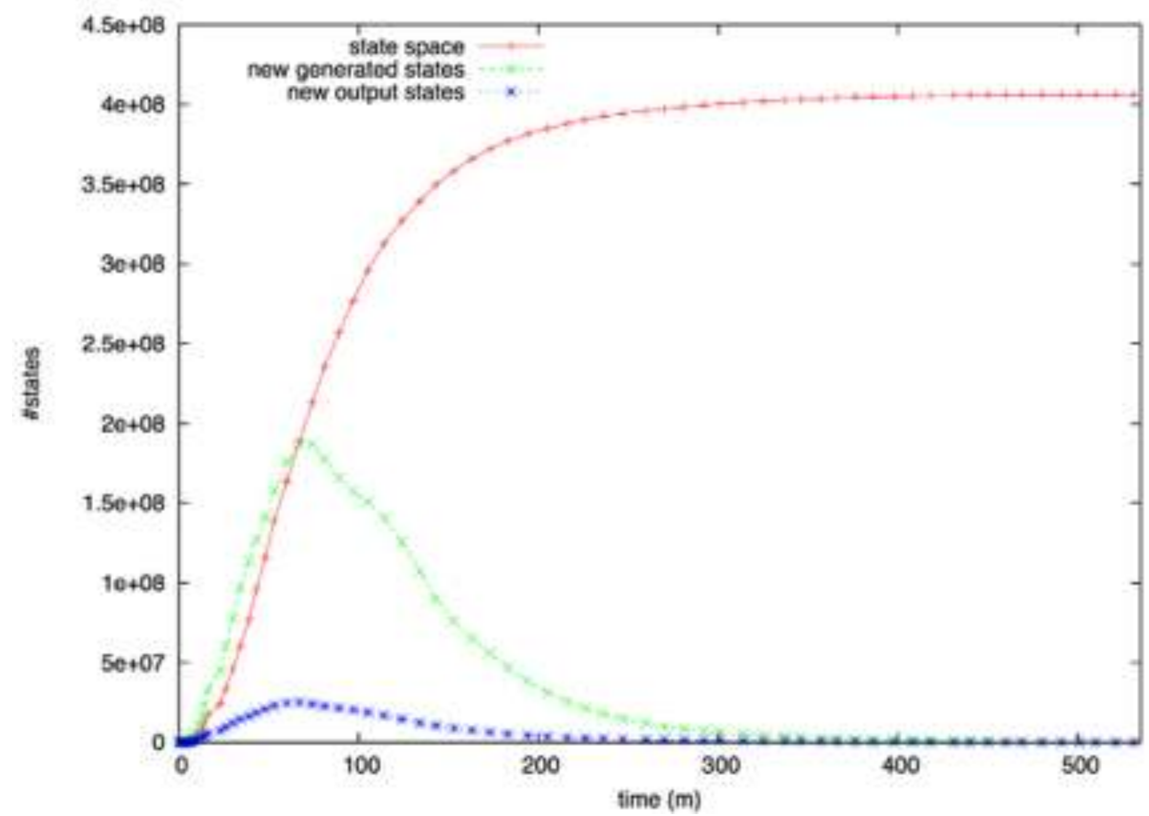
Shared Memory example:

- 1.831×10^6 reachable states
- The PIPE tool takes more than 20 hours to complete the computation.
- The adapted version takes 74 min to complete the same computation, using 16 machines.



Simple Load Balancing example:

- 4.060×10^8 states
  3.051×10^9 transitions
  120GB of data
- execution time = 530 min. using 20 machines.



CTL model checking in the cloud

- We developed a software tool which exploits the MaRDiGraS computed graphs by applying iterative map-reduce algorithms based on fixpoint characterizations of the basic temporal operators of CTL (Computational Tree Logic).
- Given a state transition system $T=\langle S,s_0,R,L\rangle$, and a set of states that satisfy the ϕ formula ($[\phi]_T$)
  - $[EX\phi]_T = R^{-}([\phi]_T)$
  - $[EG\phi]_T = \nu_X([\phi]_T \cap R^{-}(X))$
  - $[E[\phi U\psi]]_T = \mu_X([\psi]_T \cup ([\phi]_T \cap R^{-}(X)))$

Computation Tree Logic

- CTL is a branching-time logic which models time as a tree-like structure where each moment can be followed by several different possible futures. In CTL each basic temporal operator (i.e., either X, F, G) must be immediately preceded by a path quantifier (i.e., either A or E). In particular, CTL formulas are inductively defined as follows

$$\phi ::= p \mid \neg\phi \mid \phi \vee \phi \mid A\psi \mid E\psi \ (state\ formulas)$$

$$\psi ::= X\phi \mid F\phi \mid G\phi \mid \phi U \phi \ (path\ formulas)$$

- The interpretation of a CTL formula is defined over a Kripke structure (i.e, a state transition system).

Definition 1 (Kripke structure): A Kripke structure T is a quadruple $\langle S, S_0, R, L \rangle$, where:

1) S is a finite set of states.
2) S_0 is the set of initial states.
3) $R \subseteq S \times S$ is a a total transition relation, that is: $\forall s \in S\ \exists s' \in S$ such that $(s, s') \in R$
4) $L : S \rightarrow 2^{AP}$ labels each state with the set of atomic propositions that hold in that state.

Computation Tree Logic

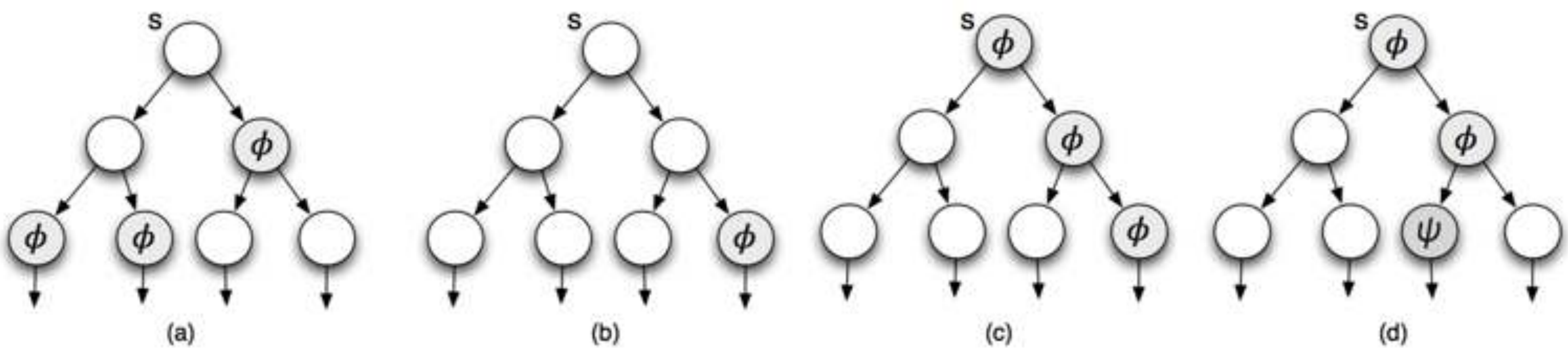


Fig. 1: (a) $T \models_s AF\phi$; (b) $T \models_s EF\phi$; (c) $T \models_s EG\phi$; (d) $T \models_s E[\phi U \psi]$

- It can be shown that any CTL formula can be written in terms of ¬, ∨, **EX**, **EG**, and **EU**

$$R^{-}(W) := \{s \in S \ : \ \exists s'(R(s,s') \wedge s' \in W)\}$$

$$[\![EX\phi]\!]_T = R^{-}([\![\phi]\!]_T)$$

greatest fixed point

$$[\![EG\phi]\!]_T = \nu_X([\![\phi]\!]_T \cap R^{-}(X))$$

monotonic predicate transformer

$$[\![E[\phi U \psi]]\!]_T = \mu_X([\![\psi]\!]_T \cup ([\![\phi]\!]_T \cap R^{-}(X)))$$

least fixed point

MapReduce EX evaluation

$$[\![EX\phi]\!]_T = R^-([\![\phi]\!]_T)$$

Algorithm 2 MapReduce algorithm for evaluating $EX\phi$

function MAP(k, s)
    if $s \in [\![\phi]\!]_T$ **then**
        for $e \in R^-(s)$ **do**
            $emit(e, \perp)$
        end for
    end if
    $emit(k, s)$
end function
function REDUCE($k, list := [s_1, s_2, ...]$)
    if $\perp \in list$ **then**
        $s := s' \in list \ s.t. \ s' \neq \perp$
        $emit(k, s)$
    end if
end function

MapReduce EG evaluation

$$[\![EG\phi]\!]_T = \nu_X([\![\phi]\!]_T \cap R^-(X))$$

Algorithm 3 MapReduce for evaluating $EG\phi$

function MAP(k, s)
    if $s \in X$ **then**
        for $e \in R^-(s)$ **do**
            $emit(e, \perp)$
        end for
    end if
    if $s \in [\![\phi]\!]_T$ **then**
        $emit(k, s)$
    end if
end function
function REDUCE($k, list := [s_1, s_2, ...]$)
    if $\perp \in list \ \wedge \ (s \neq \perp \in list)$ **then**
        $emit(k, s)$
    end if
end function

MapReduce EU evaluation

$$[\![E[\phi U \psi]]\!]_T = \mu_X([\![\psi]\!]_T \cup ([\![\phi]\!]_T \cap R^-(X)))$$

Algorithm 4 MapReduce algorithm for evaluating $E[\phi U \psi]$

function MAP(k, s)
    if $s \in X$ **then**
        for $e \in R^-(s)$ **do**
            $emit(e, \perp)$
        end for
    end if
    if $s \in [\![\phi]\!]_T \vee s \in [\![\psi]\!]_T$ **then**
        $emit(k, s)$
    end if
end function
function REDUCE$(k, list := [s_1, s_2, ...])$
    $s := s' \in list \ s.t. \ s' \neq \perp$
    if $(\perp \in list \ \wedge \ s \neq null) \vee (s \in [\![\psi]\!]_T)$ **then**
        $emit(k, s)$
    end if
end function

CTL experiments

- Models:
  - Shared memory ($\sim 10^6$ states, $\sim 10^7$ transitions)
  - Dekker ($\sim 10^7$ states, $\sim 10^8$ transitions)
  - Simple load balancing ($\sim 10^8$ states, $\sim 10^9$ transitions)

Table 1: Shared memory report

property	$\lvert [\![property]\!]_T \rvert$	# machines	time (s)
$EX[\phi]$	2.135×10^5	1	70
$EX[\phi]$	2.135×10^5	2	67
$EX[\phi]$	2.135×10^5	4	50
$EX[\phi]$	2.135×10^5	8	38
$EG[\psi]$	0	1	67
$EG[\psi]$	0	2	55
$EG[\psi]$	0	4	58
$E[\omega\ U \rho]$	1.831×10^6	1	1898
$E[\omega\ U \rho]$	1.831×10^6	2	1124
$E[\omega\ U \rho]$	1.831×10^6	4	839
$E[\omega\ U \rho]$	1.831×10^6	8	564
$E[\omega\ U \rho]$	1.831×10^6	16	509

Table 2: Dekker report

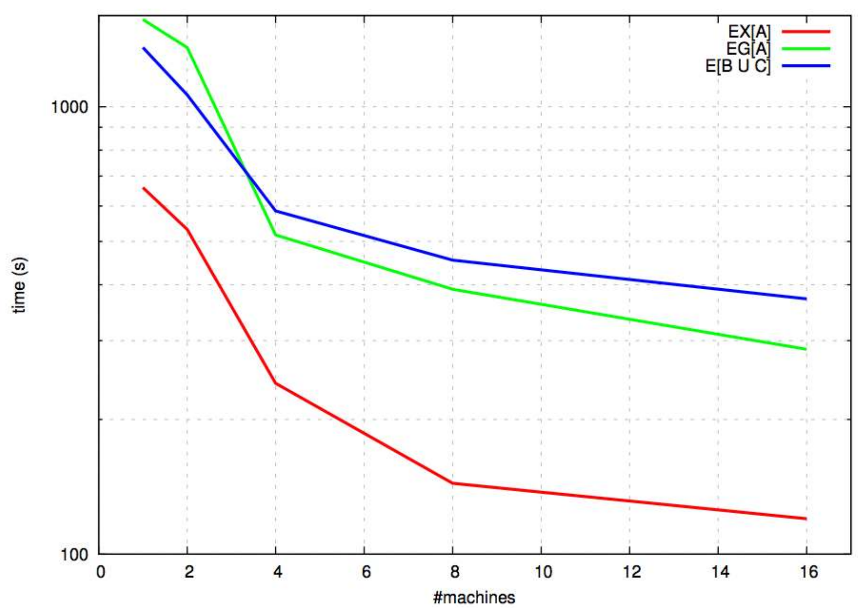
property	$\lvert [\![property]\!]_T \rvert$	# machines	time (s)
$EX[\phi]$	1.153×10^7	1	660
$EX[\phi]$	1.153×10^7	2	532
$EX[\phi]$	1.153×10^7	4	241
$EX[\phi]$	1.153×10^7	8	144
$EX[\phi]$	1.153×10^7	16	120
$EG[\psi]$	7.405×10^6	1	1567
$EG[\psi]$	7.405×10^6	2	1356
$EG[\psi]$	7.405×10^6	4	517
$EG[\psi]$	7.405×10^6	8	391
$EG[\psi]$	7.405×10^6	16	287
$E[\omega\ U \rho]$	5.767×10^6	1	1357
$E[\omega\ U \rho]$	5.767×10^6	2	1063
$E[\omega\ U \rho]$	5.767×10^6	4	585
$E[\omega\ U \rho]$	5.767×10^6	8	454
$E[\omega\ U \rho]$	5.767×10^6	16	372

Table 3: Simple load balancing report

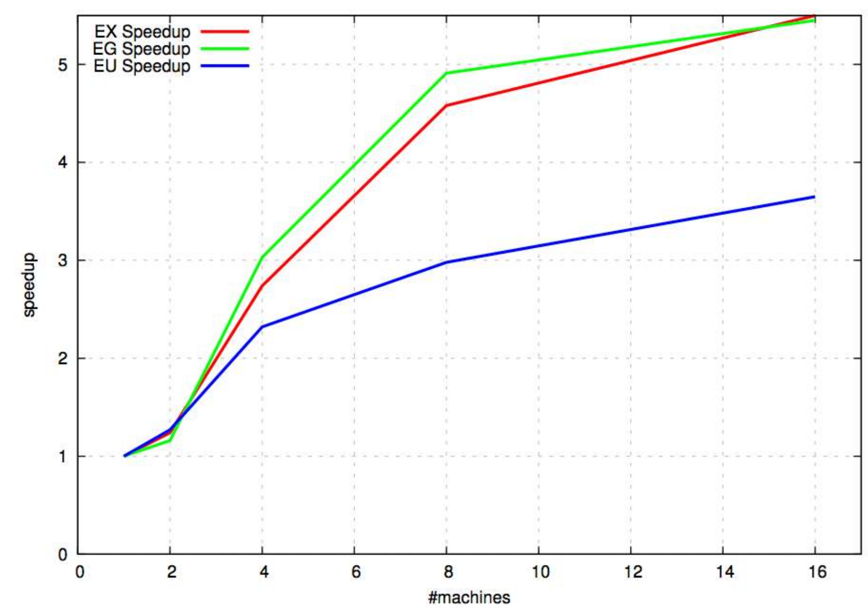
property	$\lvert [\![property]\!]_T \rvert$	# machines	time (s)
$EX[\phi]$	1.716×10^8	1	2908
$EX[\phi]$	1.716×10^8	2	2401
$EX[\phi]$	1.716×10^8	4	937
$EX[\phi]$	1.716×10^8	8	693
$EX[\phi]$	1.716×10^8	16	251
$EG[\psi]$	4.060×10^8	1	21678
$EG[\psi]$	4.060×10^8	2	17147
$EG[\psi]$	4.060×10^8	4	6525
$EG[\psi]$	4.060×10^8	8	2983
$EG[\psi]$	4.060×10^8	16	1226
$E[\omega\ U \rho]$	7.524×10^7	1	1821
$E[\omega\ U \rho]$	7.524×10^7	2	1714
$E[\omega\ U \rho]$	7.524×10^7	4	602
$E[\omega\ U \rho]$	7.524×10^7	8	377
$E[\omega\ U \rho]$	7.524×10^7	16	203

CTL experiments

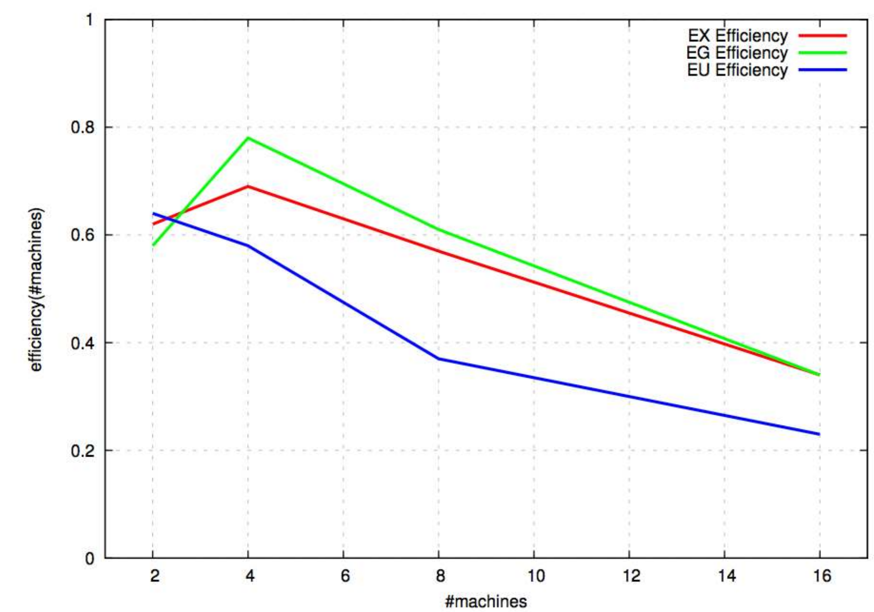
(a) Dekker model checking time



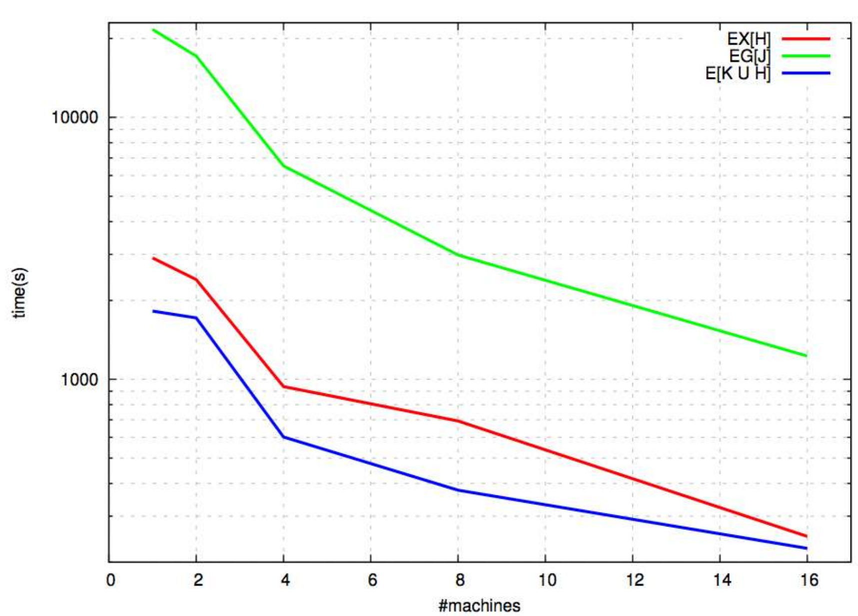
(b) Dekker Speedup



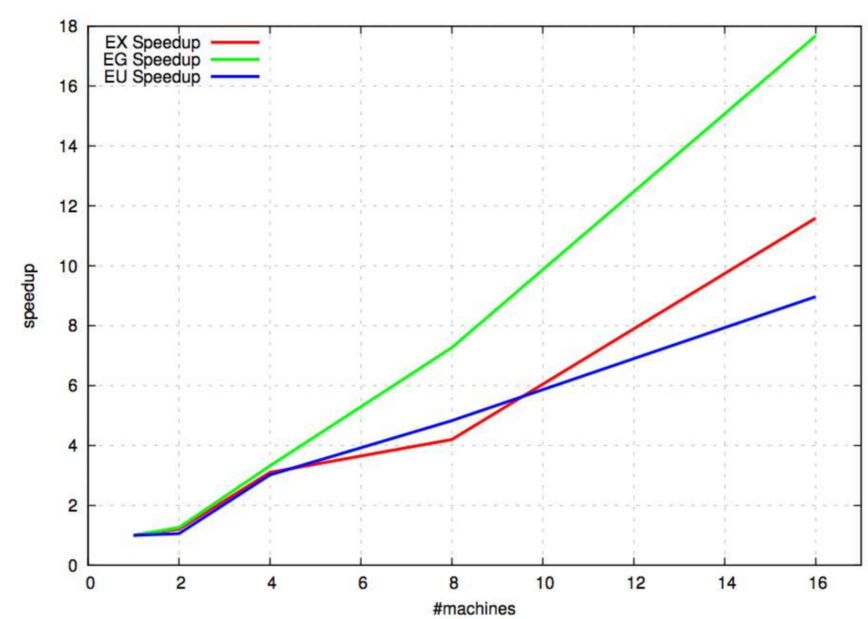
(c) Dekker efficiency



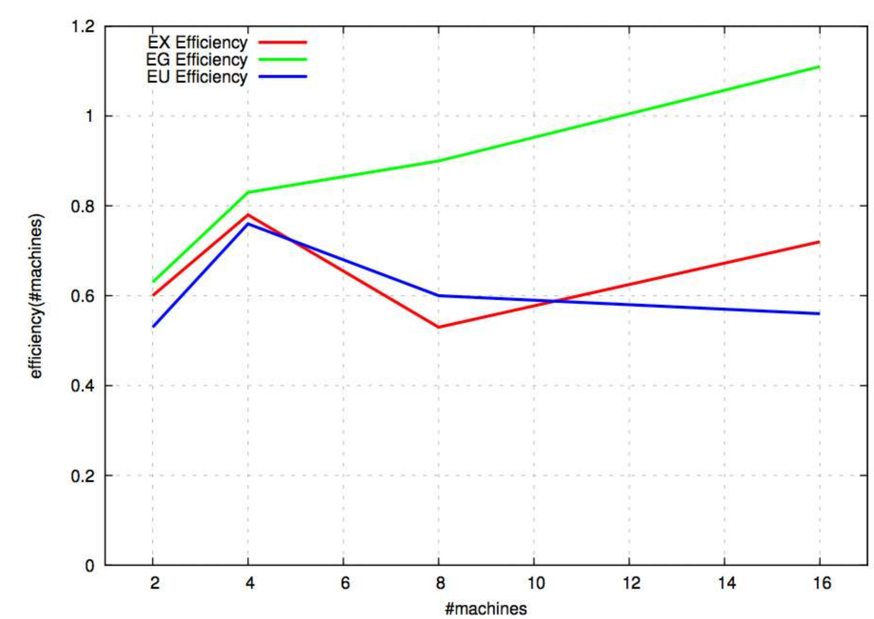
(d) Simple-lb model checking time



(e) Simple-lb Speedup



(f) Simple-lb efficiency



Conclusion

- MaRDiGraS + CTL verification in the cloud allow users to implement distributed reachability graph builders and verification tools for different formalisms without care about all non functional aspects.
    - They apply techniques typically used by the big data community and so far poorly explored for this kind of issues.
- We believe that this work could be a first step towards a synergy between two very different, but related communities: the formal verification community and the big data community.
- Open Questions
    - How it can be optimized when the remaining set gets very small?
    - How to choose the optimal threshold dynamically?
    - Are there classes of formalisms for which this approach cannot be used? And how can we adapt it to these classes?
    - ... ?

Planned Work

- Development of a technique for tackling topologically infinite TB net models
  - computation of minimal coverability sets (so far unexplored)
  - this provides a means to decide several important properties also for real time systems:
    - *coverability*: is it possible to reach a marking dominating a given marking?
    - *boundedness*: is the set of reachability markings finite?
    - *place boundedness*: is it possible to bound the number of tokens in a given place?
    - *semi-liveness*: is there a reachable marking in which a given transition is enabled?

References

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