Model Checking with the
Partial Order Reduction

Edmund M. Clarke, Jr.
Computer Science Department
Carnegie Mellon University
Pittsburgh, PA 15213
Asynchronous Computation

The interleaving model for asynchronous systems allows concurrent events to be ordered arbitrarily.

To avoid discriminating against any particular ordering, the events are interleaved in all possible ways.

The ordering between independent transitions is largely meaningless!!
The State Explosion Problem

Allowing all possible orderings is a potential cause of the state explosion problem.

To see this, consider $n$ transitions that can be executed concurrently.

In this case, there are $n!$ different orderings and $2^n$ different states (one for each subset of the transitions).

If the specification does not distinguish between these sequences, it is beneficial to consider only one with $n + 1$ states.
The partial order reduction is aimed at reducing the size of the state space that needs to be searched.

It exploits the commutativity of concurrently executed transitions, which result in the same state.

Thus, this reduction technique is best suited for asynchronous systems.

(In synchronous systems, concurrent transitions are executed simultaneously rather than being interleaved.)
The method consists of constructing a reduced state graph.

The full state graph, which may be too big to fit in memory, is never constructed.

The behaviors of the reduced graph are a subset of the behaviors of the full state graph.

The justification of the reduction method shows that the behaviors that are not present do not add any information.
The name **partial order reduction** comes from early versions of the algorithms that were based on the partial order model of program execution.

However, the method can be described better as **model checking using representatives**, since the verification is performed using representatives from the equivalence classes of behaviors.

Modified Kripke Structures

The transitions of a system play a significant role in the partial order reduction.

The partial order reduction is based on the dependency relation that exists between the transitions of a system.

Thus, we modify the definition of a Kripke structure slightly.

A state transition system is a quadruple \((S, T, S_0, L)\) where

- the set of states \(S\), the set of initial states \(S_0\), and the labeling function \(L\) are defined as for Kripke structures, and
- \(T\) is a set of transitions such that for each \(\alpha \in T\), \(\alpha \subseteq S \times S\).

A Kripke structure \(M = (S, R, S_0, L)\) may be obtained by defining \(R\) so that

\[ R(s, s') \iff \exists \alpha \in T[\alpha(s, s')] \]
A transition \( \alpha \in T \) is enabled in a state \( s \) if there is a state \( s' \) such that \( \alpha(s, s') \) holds.

Otherwise, \( \alpha \) is disabled in \( s \). The set of transitions enabled in \( s \) is \( enabled(s) \).

A transition \( \alpha \) is deterministic if for every state \( s \) there is at most one state \( s' \) such that \( \alpha(s, s') \).

When \( \alpha \) is deterministic we often write \( s' = \alpha(s) \) instead of \( \alpha(s, s') \).

Note: We will only consider deterministic transitions!
A path $\pi$ from a state $s_0$ is a finite or infinite sequence

$$\pi = s_0 \xrightarrow{\alpha_0} s_1 \xrightarrow{\alpha_1} \ldots$$

such that for every $i$, $\alpha_i(s_i, s_{i+1})$ holds.

Here, we do not require paths to be infinite. Moreover, any prefix of a path is also a path.

If $\pi$ is finite, then the length of $\pi$ is the number of transitions in $\pi$ and will be denoted by $|\pi|$.
Reduced State Graph

Goal is to reduce the number of states considered in model checking, while preserving the correctness of the property.

Will assume that a reduced state graph is first generated explicitly using depth-first search.

The model checking algorithm is then applied to the resulting state graph, which has fewer states and edges.

This speeds up the construction of the graph and uses less memory, thus resulting in a more efficient model checking algorithm.

- Actually, the reduction can be applied on-the-fly while doing the model checking.

- The DFS can also be replaced by breadth first search and combined with symbolic model checking.
Depth-First-Search Algorithm

1 \textit{hash}(s_0); \\
2 \textit{set} on\_stack(s_0); \\
3 expand\_state(s_0);

4 \textbf{procedure} expand\_state(s) \\
5 \hspace{1em} work\_set(s) := ample(s); \\
6 \hspace{1em} \textbf{while} work\_set(s) \textbf{is not empty} \textbf{do} \\
7 \hspace{2em} \textbf{let} \alpha \in work\_set(s); \\
8 \hspace{2em} work\_set(s) := work\_set(s) \setminus \{\alpha\}; \\
9 \hspace{2em} s' := \alpha(s); \\
10 \hspace{2em} \textbf{if} new(s') \textbf{then} \\
11 \hspace{3em} \textit{hash}(s'); \\
12 \hspace{3em} \textit{set} on\_stack(s'); \\
13 \hspace{3em} expand\_state(s'); \\
14 \hspace{2em} \textbf{end if}; \\
15 \hspace{2em} create\_edge(s, \alpha, s'); \\
16 \hspace{1em} \textbf{end while}; \\
17 \hspace{1em} \textit{set} completed(s); \\
18 \textbf{end procedure}
The reduction is performed by modifying the standard DFS algorithm to construct the reduced state graph.

The search starts with an initial state $s_0$ (line 1) and proceeds recursively.

For each state $s$ it selects only a subset $ample(s)$ of the enabled transitions $enabled(s)$ (in line 5).

The DFS explores only successors generated by these transitions (lines 6-16).

- The DFS algorithm constructs the reduced state graph directly.
- Constructing the full state graph and later reducing it would defy the purpose of the reduction.
Depth-First-Search Algorithm (Cont.)

When model checking is applied to the reduced state graph

- it terminates with a **positive answer** when the property holds for the original state graph.

- it produces a **counterexample**, otherwise

**Note:** The counterexample may **differ** from one obtained using the full state graph.
Ample Sets

In order to implement the algorithm we must find a systematic way of calculating $ample(s)$ for any given state $s$.

The calculation of $ample(s)$ needs to satisfy three goals:

1. **When $ample(s)$ is used instead of $enabled(s)$, enough behaviors must be retained so DFS gives correct results.**

2. **Using $ample(s)$ instead of $enabled(s)$ should result in a significantly smaller state graph.**

3. **The overhead in calculating $ample(s)$ must be reasonably small.**
An independence relation $I \subseteq T \times T$ is a symmetric, antireflexive relation such that for $s \in S$ and $(\alpha, \beta) \in I$:

**Enabledness** If $\alpha, \beta \in enabled(s)$ then $\alpha \in enabled(\beta(s))$.

**Commutativity** $\alpha, \beta \in enabled(s)$ then $\alpha(\beta(s)) = \beta(\alpha(s))$.

The dependency relation $D$ is the complement of $I$, namely

$$D = (T \times T) \setminus I.$$  

Note

- The enabledness condition states that a pair of independent transitions do not disable one another.

- However, that it is possible for one to enable another.
Potential Problems

Suppose that $\alpha$ and $\beta$ commute:

It does not matter whether $\alpha$ is executed before $\beta$ or vice versa in order to reach the state $r$ from $s$.

It is tempting to select only one of the transitions originating from $s$.

This is not appropriate for the following reasons:

**Problem 1:** The checked property might be sensitive to the choice between the states $s_1$ and $s_2$, not only the states $s$ and $r$.

**Problem 2:** The states $s_1$ and $s_2$ may have other successors in addition to $r$, which may not be explored if either is eliminated.
Visible and Invisible Transitions

Let $L : S \rightarrow 2^{AP}$ be the function that labels each state with a set of atomic propositions.

A transition $\alpha \in T$ is invisible with respect to $AP' \subseteq AP$ if for each pair $s, s' \in S$ such that $s' = \alpha(s)$,

$$L(s) \cap AP' = L(s') \cap AP'.$$

Thus, a transition is invisible when its execution from any state does not change the value of the propositional variables in $AP'$.

A transition is visible if it is not invisible.
Stuttering refers to a sequence of identically labeled states along a path in a Kripke structure.

Let \( \sigma \) and \( \rho \) be two infinite paths:

\[
\sigma = s_0 \xleftrightarrow{\alpha_0} s_1 \xleftrightarrow{\alpha_1} \ldots \quad \text{and} \quad \rho = r_0 \xleftrightarrow{\beta_0} r_1 \xleftrightarrow{\beta_1} \ldots
\]

Then \( \sigma \) and \( \rho \) are stuttering equivalent, denoted \( \sigma \sim_{st} \rho \), if there are two infinite sequences of integers

\[
0 = i_0 < i_1 < i_2 < \ldots \quad \text{and} \quad 0 = j_0 < j_1 < j_2 < \ldots
\]

such that for every \( k \geq 0 \),

\[
L(s_{i_k}) = L(s_{i_{k+1}}) = \ldots = L(s_{i_{k+1}-1}) = \\
L(r_{j_k}) = L(r_{j_{k+1}}) = \ldots = L(r_{j_{k+1}-1}).
\]

Stuttering equivalence can be defined similarly for finite paths.
A finite sequence of identically labeled states is called a block.

Intuitively, Two paths are stuttering equivalent if they can be partitioned into blocks, so states in the $k$th block of one are labeled the same as states in the $k$th block of the other.

Note: Corresponding blocks may have different lengths!
Consider the diagram used to illustrate commutativity again.

Suppose that at least one transition, say $\alpha$, is invisible, then $L(s) = L(s_1)$ and $L(s_2) = L(r)$.

Consequently,

$$ss_1r \sim_{st} ss_2r$$

Note: The paths $ss_1r$ and $ss_2r$ are stuttering equivalent!!
An LTL formula $\mathbf{A} f$ is invariant under stuttering if and only if for each pair of paths $\pi$ and $\pi'$ such that $\pi \sim_{st} \pi'$,

\[ \pi \models f \text{ if and only if } \pi' \models f. \]

We denote the subset of the logic LTL without the next time operator by $\text{LTL}_{-X}$.

**Theorem.** Any $\text{LTL}_{-X}$ property is invariant under stuttering.
Stuttering Equivalent Structures

Without loss of generality, assume that $M$ has initial state $s_0$ and that $M'$ has initial state $s'_0$.

Then the two structures $M$ and $M'$ are stuttering equivalent if and only if

- For each path $\sigma$ of $M$ that starts in $s_0$ there is a path $\sigma'$ of $M'$ starting in $s'_0$ such that $\sigma \sim_{st} \sigma'$.
- For each path $\sigma'$ of $M'$ that starts in $s'_0$ there is a path $\sigma$ of $M$ starting in $s_0$ such that $\sigma' \sim_{st} \sigma$.

**Corollary.** Let $M$ and $M'$ be two stuttering equivalent structures. Then, for every LTL$_X$ property $A\ f$

\[ M, \ s_0 \models f \ \text{if and only if} \ M', \ s'_0 \models A\ f. \]
Commutativity and invisibility allow us to avoid generating some of the states when the specification is invariant under stuttering.

Based on this observation, it is possible to devise a systematic way of selecting an ample set for any given state.

The ample sets will be used by the DFS algorithm to construct a reduced state graph so that for every path not considered there is a stuttering equivalent path that is considered.

This guarantees that the reduced state graph is stuttering equivalent to the full state graph.

We say that state \( s \) is fully expanded when

\[
ample(s) = enabled(s).
\]

In this case, all of the successors of that state will be explored by the DFS algorithm.
Correctness of Reduction

Will state four conditions for selecting $ample(s) \subseteq enabled(s)$ so satisfaction of the $LTL_{X}$ specifications is preserved.

The reduction will depend on the set of propositions $AP'$ that appear in the $LTL_{X}$ formula.

Condition C0 is very simple:

$$C_0 \quad ample(s) = \emptyset \text{ if and only if } enabled(s) = \emptyset.$$ 

Intuitively, if the state has at least one successor, then the reduced state graph also contains a successor for this state.
Condition $\textbf{C1}$ is the most complicated constraint.

$\textbf{C1}$ Along every path in the full state graph that starts at $s$, the following condition holds:

A transition that is dependent on a transition in $\text{ample}(s)$ can not be executed without one in $\text{ample}(s)$ occurring first.

Note that Condition $\textbf{C1}$ refers to paths in the full state graph.

Obviously, we need a way of checking that $\textbf{C1}$ holds without actually constructing the full state graph.

Later, we will show how to restrict $\textbf{C1}$ so that $\text{ample}(s)$ can be calculated based on the current state $s$. 
**Lemma.** The transitions in $\text{enabled}(s) \setminus \text{ample}(s)$ are all independent of those in $\text{ample}(s)$.

**Proof:**

Let $\gamma \in \text{enabled}(s) \setminus \text{ample}(s)$.

Suppose that $(\gamma, \delta) \in D$, where $\delta \in \text{ample}(s)$.

Since $\gamma$ is enabled in $s$, there is a path starting with $\gamma$ in the full graph.

But then a transition dependent on some transition in $\text{ample}(s)$ is executed before a transition in $\text{ample}(s)$.

This contradicts condition C1. □
If we always choose the next transition from \( \text{ample}(s) \), we will not omit any paths that are essential for correctness.

**Condition C1** implies that such a path will have one of two forms:

- The path has a prefix \( \beta_0\beta_1 \ldots \beta_m\alpha \), where \( \alpha \in \text{ample}(s) \) and each \( \beta_i \) is independent of all transitions in \( \text{ample}(s) \) including \( \alpha \).

- The path is an infinite sequence of transitions \( \beta_0\beta_1 \ldots \) where each \( \beta_i \) is independent of all transitions in \( \text{ample}(s) \).
Correctness of Reduction (Cont.)

If along a sequence of transitions $\beta_0\beta_1 \ldots \beta_m$ executed from $s$,

If none of the transitions in $ample(s)$ have occurred, then all the transitions in $ample(s)$ remain enabled.

This is because each $\beta_i$ is independent of the transitions in $ample(s)$ and, therefore, cannot disable them.
In the first case, assume that the sequence of transitions $\beta_0\beta_1 \ldots \beta_m\alpha$ reaches a state $r$.

This sequence will not be considered by the DFS algorithm.

By applying the enabledness and commutativity conditions $m$ times, we can construct a sequence $\alpha\beta_0\beta_1 \ldots \beta_m$, that also reaches $r$.

Thus, if the reduced state graph does not contain the sequence $\beta_0\beta_1 \ldots \beta_m\alpha$ that reaches $r$, we can construct from $s$ another sequence that reaches $r$. 

![Diagram](image-url)
Another Correctness Conditions

Consider the two sequences of states:

- \( \sigma = s_0s_1 \ldots s_mr \) generated by \( \beta_0\beta_1 \ldots \beta_m\alpha \), and
- \( \rho = sr_0r_1 \ldots r_m \) generated by \( \alpha\beta_0\beta_1 \ldots \beta_m \).

In order to discard \( \sigma \), we want \( \sigma \) and \( \rho \) to be stuttering equivalent.

This is guaranteed if \( \alpha \) is invisible, since then \( L(s_i) = L(r_i) \) for \( 0 \leq i \leq m \).

Thus, the checked property will not be able to distinguish between the two sequences above.

\( \textbf{C2} \) If \( s \) is not fully expanded, then every \( \alpha \in \text{ample}(s) \) is invisible.

- This condition is called invisibility.
Now consider the case in which an infinite path $\beta_0\beta_1\beta_2\ldots$ that starts at $s$ does not include any transition from $ample(s)$.

By Condition C2 all transitions in $ample(s)$ are invisible. Let $\alpha$ be such a transition.

Then the path generated by the sequence $\alpha\beta_0\beta_1\beta_2\ldots$ is stuttering equivalent to the one generated by $\beta_0\beta_1\beta_2\ldots$.

Again, even though the path $\beta_0\beta_1\beta_2\ldots$ is not in the reduced state graph, a stuttering equivalent path is included.
Problem with Correctness Condition

C1 and C2 are not yet sufficient to guarantee that the reduced state graph is stuttering equivalent to the full state graph.

In fact, there is a possibility that some transition will actually be delayed forever because of a cycle in the constructed state graph.

Assume that $\beta$ is independent of the transitions $\alpha_1$, $\alpha_2$ and $\alpha_3$ and that $\alpha_1$, $\alpha_2$ and $\alpha_3$ are interdependent.

The process on the left can execute the $\beta$ exactly once.

Assume there is one proposition $p$, which is changed from True to False by $\beta$, so that $\beta$ is visible.

The process on the right performs the invisible transitions $\alpha_1$, $\alpha_2$ and $\alpha_3$ repeatedly in a loop.
The full state graph of the system is shown below:

Starting with the initial state $s_1$, we can select $ample(s_1) = \{ \alpha_1 \}$ and generate $s_2 = \alpha_1(s_1)$.

Next, we can select $ample(s_2) = \{ \alpha_2 \}$ and generate $s_3 = \alpha_2(s_2)$.

When we reach $s_3$, we can select $ample(s_3) = \{ \alpha_3 \}$ and close the cycle $(s_1, s_2, s_3)$.

(Easy to see that C0, C1 and C2 are satisfied at each step.)

But, the reduced state graph does not contain any sequences where $p$ is changed from True to False!!
Cycle Closing Condition

Note that at each state on the cycle \((s_1, s_2, s_3, s_1)\) \(\beta\) is deferred to a possible future state.

When the cycle is closed, the construction terminates, and transition \(\beta\) is ignored!!

To prevent this situation from occurring we need one more condition:

**C3** A cycle is not allowed if it contains a state in which some transition \(\alpha\) is enabled, but is never included in \(ample(s)\) for any state \(s\) on the cycle.

Condition **C3** is called the **Cycle closing condition**.
Consider the diagram used to illustrate commutativity of actions.

Assume that the DFS reduction algorithm chooses $\beta$ as $ample(s)$ and does not include state $s_1$ in the reduced graph.

By Condition C2, $\beta$ must be invisible; thus $s, s_2, r$ and $s, s_1, r$ are stuttering equivalent.

Since we are only interested in stuttering invariant properties, we can’t distinguish between the two sequences.
Problem 2 Again

Assume that there is a transition $\gamma$ enabled from $s_1$.

Note that $\gamma$ cannot be dependent on $\beta$. Otherwise, the sequence $\alpha, \gamma$ violates C1.

Thus, $\gamma$ is independent of $\beta$. Since it is enabled in $s_1$, it must also be enabled in state $r$.

Assume that $\gamma$, when executed from $r$, results in state $r'$ and when executed from $s_1$ results in state $s'_1$.

Since $\beta$ is invisible, the two state sequences $s, s_1, s'_1$ and $s, s_2, r, r'$ are stuttering equivalent.

Therefore, properties that are invariant under stuttering will not distinguish between the two.
We assume that the concurrent program is composed of processes and that each process has a program counter.

- \( pc_i(s) \) will denote the program counter of a process \( P_i \) in a state \( s \).

- \( pre(\alpha) \) is a set of transitions that includes the transitions whose execution may enable \( \alpha \).

- \( dep(\alpha) \) is the set of transitions that are dependent on \( \alpha \).

- \( T_i \) is the set of transitions of process \( P_i \).

- \( T_i(s) = T_i \cap enabled(s) \) denotes the set of transitions of \( P_i \) that are enabled in the state \( s \).

- \( current_i(s) \) is the set of transitions of \( P_i \) that are enabled in some state \( s' \) such that \( pc_i(s') = pc_i(s) \).
We now describe the dependency relation for the different models of computation.

- Pairs of transitions that share a variable, which is changed by at least one of them, are dependent.

- Pairs of transitions belonging to the same process are dependent.

- Two send transitions that use the same message queue are dependent. Similarly, two receive transitions are dependent.

Note that a transition that involves handshaking or rendezvous communication as in CSP or ADA can be treated as a joint transition of both processes. Therefore, it depends on all of the transitions of both processes.
An obvious candidate for \( ample(s) \) is the set \( T_i(s) \) of transitions enabled in \( s \) for some process \( P_i \).

- Since the transitions in \( T_i(s) \) are interdependent, an ample set for \( s \) must include either all of the transitions or none of them.

- To construct an ample set for the current state \( s \), we start with some process \( P_i \) such that \( T_i(s) \neq \emptyset \).

- We want to check whether \( ample(s) = T_i(s) \) satisfies Condition \( C1 \).

- There are two cases in which this selection might violate \( C1 \).

- In both of these cases, some transitions independent of those in \( T_i(s) \) are executed, eventually enabling a transition \( \alpha \) that is dependent on \( T_i(s) \).

- The independent transitions in the sequence cannot be in \( T_i \), since all the transitions of \( P_i \) are interdependent.
In the first case, $\alpha$ belongs to some other process $P_j$.

A necessary condition for this to happen is that $\text{dep}(T_i(s))$ includes a transition of process $P_j$.

By examining the dependency relation, this condition can be checked effectively.
In the second case, $\alpha$ belongs to $P_i$. Suppose that the transition $\alpha \in T_i$ which violates $C1$ is executed from a state $s'$.

- The transitions executed on the path from $s$ to $s'$ are independent of $T_i(s)$ and hence, are from other processes.
- Therefore, $pc_i(s') = pc_i(s)$. So $\alpha$ must be in $current_i(s)$.
- In addition, $\alpha \not\in T_i(s)$, otherwise it does not violate $C1$.
- Thus, $\alpha \in current_i(s) \setminus T_i(s)$.
- Since $\alpha$ is not in $T_i(s)$, it is disabled in $s$.
- Therefore, a transition in $pre(\alpha)$ must be included in the sequence from $s$ to $s'$.

Thus, a necessary condition is that $pre(current_i(s) \setminus T_i(s))$ includes transitions of processes other than $P_i$.

This condition can also be checked effectively.
If all else fails . . .

In both cases we discard $T_i(s)$ and try the transitions $T_j(s)$ of another process $j$ as a candidate for ample$(s)$.

Note: We take a conservative approach discarding some ample sets even though at run-time C1 might not actually be violated.