

Model Checking μ -Calculus

(Based on [Clarke et al. 1999])

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Introduction

- 🌐 The **propositional μ -calculus** is a powerful language for expressing properties of transition systems by using **least** and **greatest fixpoint** operators.
- 🌐 It has gained much attention for two reasons:
 - ☀️ Many temporal and program logics can be encoded into the μ -calculus.
 - ☀️ There exist efficient model checking algorithms for this formalism.
- 🌐 Widespread use of BDDs made fixpoint-based algorithms even more important.

Introduction (cont.)

🌐 Model checking algorithms for the μ -calculus fall into two categories:

☀️ **Local procedures:**

- 👁️ for proving that *a specific state* satisfies the given formula
- 👁️ not having been combined with BDDs

☀️ **Global procedures:**

- 👁️ for proving that *all states* in a set satisfy the given formula
- 👁️ those based on BDDs prove to be very efficient in practice

🌐 Here, we consider only global model checking.

Extended Kripke Structures

- 🌐 Formulae in the μ -calculus are interpreted relative to a transition system.
- 🌐 To distinguish between different transitions in a system, we modify the definition of a Kripke structure slightly.
- 🌐 An *extended Kripke structure* M over AP is a tuple $\langle S, T, L \rangle$:
 - ☀ S is a nonempty set of states,
 - ☀ T is a set of transition relations, and
 - ☀ $L : S \rightarrow 2^{AP}$ gives the set of atomic propositions true in a state.
- 🌐 We will refer to each $a \in T$, $a \subseteq S \times S$, as a *transition* (instead of a transition relation).

- Let $VAR = \{Q, Q_1, Q_2, \dots\}$ be a set of *relational variables* (representing unary predicates).
- Each relational variable $Q \in VAR$ can be assigned a subset of S .
- The μ -calculus formulae are constructed as follows:
 - If $p \in AP$, then p is a formula.
 - A relational variable is a formula.
 - If f and g are formulae, then $\neg f$, $f \wedge g$, $f \vee g$ are formulae.
 - If f is a formula and $a \in T$, then $\langle a \rangle f$ and $[a]f$ are formulae.
 - If $Q \in VAR$ and f is a *syntactically monotone* formula in Q , then $\mu Q.f$ and $\nu Q.f$ are formulae.

Syntactically Monotone Formulae

- A formula f is *syntactically monotone* in Q if all occurrences of Q within f fall under *an even number of negations* in f .
- Consider these formulae:

$$f_1 = \neg((p \vee \neg Q_1) \wedge \neg \langle a \rangle Q_1)$$

$$f_2 = (Q_1 \wedge \langle a \rangle Q_1) \vee \neg(p \wedge [a] Q_2)$$

- f_1 is syntactically monotone in Q_1 .
- f_2 is syntactically monotone in Q_1 , but not syntactically monotone in Q_2 .

- 🌐 The formula $\langle a \rangle f$ means that f holds in **at least one** state reachable in one step by making an a -transition.
- 🌐 The formula $[a]f$ means that f holds in **all** states reachable in one step by making an a -transition.
- 🌐 The formula $\mu Q.f(Q)$ expresses the **least fixpoint** of f .
- 🌐 The formula $\nu Q.f(Q)$ expresses the **greatest fixpoint** of f .
- 🌐 The fixpoint operator behaves like a quantifier in first-order logic.
- 🌐 Variables can be **free** or **bound** by a fixpoint operator.
- 🌐 We write $f(Q_1, Q_2, \dots, Q_n)$ to emphasize that a formula f contains free relational variables Q_1, Q_2, \dots, Q_n .

- 🌐 We write $s \xrightarrow{a} s'$ to mean $(s, s') \in a$.
- 🌐 The *environment* $e : VAR \rightarrow 2^S$ is an interpretation for free variables.
- 🌐 We denote by $e[Q \leftarrow W]$ a new environment that is the same as e except that $e[Q \leftarrow W](Q) = W$.
- 🌐 A formula f is interpreted as a set of states in which f is true, denoted $\llbracket f \rrbracket_M e$, where
 - ☀️ M is a transition system and
 - ☀️ e is an environment.

μ -Calculus: Semantics (cont.)

- [[p]] $_{Me} = \{s \mid p \in L(s)\}$
- [[Q]] $_{Me} = e(Q)$
- [[$\neg f$]] $_{Me} = S \setminus [[f]]_{Me}$
- [[$f \wedge g$]] $_{Me} = [[f]]_{Me} \cap [[g]]_{Me}$
- [[$f \vee g$]] $_{Me} = [[f]]_{Me} \cup [[g]]_{Me}$
- [[$\langle a \rangle f$]] $_{Me} = \{s \mid \exists t[s \xrightarrow{a} t \text{ and } t \in [[f]]_{Me}]\}$
- [[$[a]f$]] $_{Me} = \{s \mid \forall t[s \xrightarrow{a} t \text{ implies } t \in [[f]]_{Me}]\}$
- [[$\mu Q.f$]] $_{Me}$ is the least fixpoint of the predicate transformer $\tau : 2^S \rightarrow 2^S$, where $\tau(W) = [[f]]_{Me}[Q \leftarrow W]$
- [[$\nu Q.f$]] $_{Me}$ is the greatest fixpoint of the predicate transformer $\tau : 2^S \rightarrow 2^S$, where $\tau(W) = [[f]]_{Me}[Q \leftarrow W]$

An Example

Let $f = p \wedge [a]Q$. Formula f defines a predicate transformer τ as follows.

$$\begin{aligned}\tau(W) &= \llbracket f \rrbracket_{Me}[Q \leftarrow W] \\ &= \llbracket p \wedge [a]Q \rrbracket_{Me}[Q \leftarrow W] \\ &= \llbracket p \rrbracket_{Me}[Q \leftarrow W] \cap \llbracket [a]Q \rrbracket_{Me}[Q \leftarrow W] \\ &= \{s \mid p \in L(s)\} \cap \\ &\quad \{s \mid \forall t (s \xrightarrow{a} t \text{ implies } t \in \llbracket Q \rrbracket_{Me}[Q \leftarrow W])\} \\ &= \{s \mid p \in L(s)\} \cap \\ &\quad \{s \mid \forall t (s \xrightarrow{a} t \text{ implies } t \in W)\}\end{aligned}$$

A CTL Formula in μ -Calculus

- Consider **EG** f with fairness constraint k .
- Recall that this property can be expressed as a fixpoint:

$$\nu Z . f \wedge \mathbf{EX} \mathbf{E}[f \mathbf{U} (Z \wedge k)].$$

- Using the fixpoint characterization of **EU**, we obtain

$$\mathbf{E}[f \mathbf{U} (Z \wedge k)] = \mu Y . (Z \wedge k) \vee (f \wedge \mathbf{EX} Y).$$

- Substituting the right-hand side of the second formula in the first one gives

$$\nu Z . f \wedge \mathbf{EX} (\mu Y . (Z \wedge k) \vee (f \wedge \mathbf{EX} Y)).$$

A CTL Formula in μ -Calculus (cont.)

- Suppose the system under consideration has just one transition a .
- Replace **EX** by $\langle a \rangle$, we obtain the μ -calculus formula

$$\nu Z . f \wedge \langle a \rangle (\mu Y . (Z \wedge k) \vee (f \wedge \langle a \rangle Y)).$$

Negation and Monotonicity

- 🌐 All negations can be pushed down to the atomic propositions:

$$\begin{aligned}\neg[a]f &\equiv \langle a \rangle \neg f \\ \neg \langle a \rangle f &\equiv [a] \neg f \\ \neg \mu Q. f(Q) &\equiv \nu Q. \neg f(\neg Q) \\ \neg \nu Q. f(Q) &\equiv \mu Q. \neg f(\neg Q)\end{aligned}$$

- 🌐 Every logical connective except negation is monotonic.
- 🌐 Bound variables are under an even number of negations, thus they can be made negation-free.
- 🌐 Therefore, each possible formula in a fixpoint operator is monotonic.
- 🌐 This ensures the existence of the fixpoints.

Fixpoint Reviewed

- Let $\tau : 2^S \rightarrow 2^S$ be a monotonic function.
- If S is finite and τ is monotonic, then τ is also \cup -continuous and \cap -continuous.
- $\mu Q.\tau(Q) = \bigcup_i \tau^i(\text{False})$, i.e., $\mu Q.\tau(Q)$ is the union of the following ascending chain of approximations:

$$\text{False} \subseteq \tau(\text{False}) \subseteq \tau^2(\text{False}) \subseteq \dots \subseteq \tau^n(\text{False}) \subseteq \dots$$

- $\nu Q.\tau(Q) = \bigcap_i \tau^i(\text{True})$, i.e., $\nu Q.\tau(Q)$ is the intersection of the following descending chain of approximations:

$$\text{True} \supseteq \tau(\text{True}) \supseteq \tau^2(\text{True}) \supseteq \dots \supseteq \tau^n(\text{True}) \supseteq \dots$$

Naive Algorithm

```
1  function Eval( $f$ ,  $e$ )
2  if  $f = p$  then return  $\{s \mid p \in L(s)\}$ ;
3  if  $f = Q$  then return  $e(Q)$ ;
4  if  $f = g_1 \wedge g_2$  then
5      return Eval( $g_1$ ,  $e$ )  $\cap$  Eval( $g_2$ ,  $e$ );
6  if  $f = g_1 \vee g_2$  then
7      return Eval( $g_1$ ,  $e$ )  $\cup$  Eval( $g_2$ ,  $e$ );
8  if  $f = \langle a \rangle g$  then
9      return  $\{s \mid \exists t (s \xrightarrow{a} t \text{ and } t \in \text{Eval}(g, e))\}$ ;
10 if  $f = [a]g$  then
11     return  $\{s \mid \forall t (s \xrightarrow{a} t \text{ implies } t \in \text{Eval}(g, e))\}$ ;
12 if  $f = \mu Q.g(Q)$  then return Lfp( $g$ ,  $e$ ,  $Q$ );
13 if  $f = \nu Q.g(Q)$  then return Gfp( $g$ ,  $e$ ,  $Q$ );
14 end function
```


Naive Least Fixpoint Procedure

```
1  function Lfp( $g, e, Q$ )
2   $Q_{\text{val}} \leftarrow \text{False};$ 
3  repeat
4   $Q_{\text{old}} \leftarrow Q_{\text{val}};$ 
5   $Q_{\text{val}} \leftarrow \text{Eval}(g, e[Q \leftarrow Q_{\text{val}}]);$ 
6  until  $Q_{\text{val}} = Q_{\text{old}};$ 
7  return  $Q_{\text{val}};$ 
8  end function
```

Naive Greatest Fixpoint Procedure

```
1  function Gfp( $g, e, Q$ )
2   $Q_{\text{val}} \leftarrow \text{True};$ 
3  repeat
4   $Q_{\text{old}} \leftarrow Q_{\text{val}};$ 
5   $Q_{\text{val}} \leftarrow \text{Eval}(g, e[Q \leftarrow Q_{\text{val}}]);$ 
6  until  $Q_{\text{val}} = Q_{\text{old}}$ 
7  return  $Q_{\text{val}};$ 
8  end function
```

A Run Sketch

- 🌐 Consider the calculation of $\mu Q_1.g_1(Q_1, \mu Q_2.g_2(Q_1, Q_2))$.
- 🌐 We start with the initial approximation $Q_1^0 = False$.
 - ☀️ Compute the inner fixpoint starting from $Q_2^{00} = False$ until we reach the fixpoint $Q_2^{0\omega}$.
- 🌐 Q_1 is increased to $Q_1^1 = g_1(Q_1^0, Q_2^{0\omega})$.
 - ☀️ Compute the inner fixpoint starting from $Q_2^{10} = False$ until we reach the fixpoint $Q_2^{1\omega}$.
- 🌐 Q_1 is increased to $Q_1^2 = g_1(Q_1^1, Q_2^{1\omega})$.
- 🌐 ...
- 🌐 This continues until we reach the fixpoint Q_1^ω .

A Run Sketch (cont.)

🌐 Summary of the calculation of $\mu Q_1.g_1(Q_1, \mu Q_2.g_2(Q_1, Q_2))$:

Q_1^0 $= \text{False}$	$Q_2^{00} \quad Q_2^{01} \quad \dots \quad Q_2^{0\omega}$ $= \text{False}; = g_2(Q_1^0, Q_2^{00});$
Q_1^1 $= g_1(Q_1^0, Q_2^{0\omega})$	$Q_2^{10} \quad Q_2^{11} \quad \dots \quad Q_2^{1\omega}$ $= \text{False}; = g_2(Q_1^1, Q_2^{10});$
\vdots	\vdots
$Q_1^{\omega-2}$ $= g_1(Q_1^{\omega-3}, Q_2^{(\omega-3)\omega})$	$Q_2^{(\omega-2)0} \quad Q_2^{(\omega-2)1} \quad \dots \quad Q_2^{(\omega-2)\omega}$ $= \text{False}; = g_2(Q_1^{\omega-2}, Q_2^{(\omega-2)0});$
$Q_1^{\omega-1}$ $= g_1(Q_1^{\omega-2}, Q_2^{(\omega-2)\omega})$	$Q_2^{(\omega-1)0} \quad Q_2^{(\omega-1)1} \quad \dots \quad Q_2^{(\omega-1)\omega}$ $= \text{False}; = g_2(Q_1^{\omega-1}, Q_2^{(\omega-1)0});$
Q_1^ω $= g_1(Q_1^{\omega-1}, Q_2^{(\omega-1)\omega})$	

Complexity Analysis

- Let k be the maximum nesting depth of fixpoint operators.
- The naive algorithm runs in $O(|M| \cdot |f| \cdot n^k)$ time, where M is the Kripke structure and n the number of states. (Note: for $M = (S, T, L)$, $|M| = |S| + \sum_{a \in T} |a|$ and $n = |S|$.)
 - The innermost fixpoint will be evaluated $O(n^k)$ times.
 - Each individual iteration takes $O(|M| \cdot |f|)$ steps.

Alternation Depth

- 🌐 Top-level ν -subformula of f : a subformula $\nu Q.g$ that is not contained within any other greatest fixpoint subformula of f .
- 🌐 The top-level μ -subformula of f is defined analogously.
- 🌐 The *alternation depth* of a formula f is the largest number of alternations in the nesting of least and greatest fixpoints for a same variable in f , denoted $d(f)$:
 - ☀️ $d(p) = d(Q) = 0$
 - ☀️ $d(f \wedge g) = d(f \vee g) = \max(d(f), d(g))$
 - ☀️ $d(\langle a \rangle f) = d([a]f) = d(f)$
 - ☀️ $d(\mu Q.f) = \max(1, d(f), 1 + \max(\{d(g) \mid g \text{ is a top level } \nu\text{-subformula of } f \text{ with } Q \text{ as a free variable}\}))$
 - ☀️ $d(\nu Q.f) = \max(1, d(f), 1 + \max(\{d(g) \mid g \text{ is a top level } \mu\text{-subformula of } f \text{ with } Q \text{ as a free variable}\}))$

Alternation Depth (cont.)

🌐 Examples:

$$\text{☀} d(p \wedge [a]Q) = 0$$

$$\text{☀} d(\mu Q.p \vee \langle a \rangle Q) = 1$$

$$\text{☀} d(\nu Q_1.(\nu Q_2.(p \wedge [a]Q_2)) \wedge \langle a \rangle Q_1) = 1$$

$$\text{☀} d(\nu Q_1.(\mu Q_2.(p \vee \langle a \rangle Q_2)) \wedge \langle a \rangle Q_1) = 1$$

$$\text{☀} d(\nu Q_1.\mu Q_2.(p \wedge \langle a \rangle Q_1) \vee \langle a \rangle Q_2) = 2$$

🌐 Recall that, for a system with a single transition a and fairness constraint k , the μ -calculus formula corresponding to **EG** f is

$$\nu Z . f \wedge \langle a \rangle (\mu Y . (Z \wedge k) \vee (f \wedge \langle a \rangle Y)).$$

This formula has an alternation depth of two.

A Better Algorithm

- 🌐 An algorithm by Emerson and Lei demonstrates that the value of a fixpoint formula can be computed with $O((|f| \cdot n)^d)$ iterations, where d is the alternation depth of f .
- 🌐 The basic idea exploits sequences of fixpoints that have the same type to reduce the complexity of the algorithm.
- 🌐 It is unnecessary to re-initialize computations of inner fixpoints with *False* or *True*.
- 🌐 Instead, to compute a least fixpoint, it is enough to start iterating with **any approximation** known to be **below** the fixpoint.

Lemma 22

- 🌐 Let $\tau : 2^S \rightarrow 2^S$ be monotonic and S be finite.
- 🌐 If $W \subseteq \bigcup_i \tau^i(\text{False})$, then $\bigcup_i \tau^i(W) = \bigcup_i \tau^i(\text{False})$.
- 🌐 Proof:
 - ☀️ $\bigcup_i \tau^i(W) \subseteq \bigcup_i \tau^i(\text{False})$:

$$\begin{array}{l}
 W \subseteq \bigcup_i \tau^i(\text{False}) \\
 \tau(W) \subseteq \tau(\bigcup_i \tau^i(\text{False})) = \bigcup_i \tau^i(\text{False}) \\
 \vdots \\
 \tau^n(W) \subseteq \bigcup_i \tau^i(\text{False}) \\
 \vdots \\
 \hline
 \bigcup_i \tau^i(W) \subseteq \bigcup_i \tau^i(\text{False})
 \end{array}$$

Lemma 22 (cont.)

🌐 $\bigcup_i \tau^i(\text{False}) \subseteq \bigcup_i \tau^i(W)$:

$$\begin{array}{rcl} \text{False} & \subseteq & W = \tau^0(W) \\ \tau(\text{False}) & \subseteq & \tau(W) \\ & \vdots & \\ \tau^n(\text{False}) & \subseteq & \tau^n(W) \\ & \vdots & \\ \hline \bigcup_i \tau^i(\text{False}) & \subseteq & \bigcup_i \tau^i(W) \end{array}$$

🌐 So, to compute a least fixpoint, it is enough to **start iterating with any approximation below the fixpoint.**

A Better Run Sketch

- 🌐 Consider the calculation of $\mu Q_1.g_1(Q_1, \mu Q_2.g_2(Q_1, Q_2))$.
- 🌐 We start with the initial approximation $Q_1^0 = False$.
- 🌐 When computing $Q_2^{i\omega}$, we always begin with $Q_2^{i0} = Q_2^{(i-1)\omega}$.
 - ☀️ Compute the inner fixpoint starting from $Q_2^{00} = False$ until we reach the fixpoint $Q_2^{0\omega}$.
 - ☀️ Q_1 is increased to $Q_1^1 = g_1(Q_1^0, Q_2^{0\omega})$.
 - ☀️ Compute the inner fixpoint starting from $Q_2^{10} = Q_2^{0\omega}$ until we reach the fixpoint $Q_2^{1\omega}$.
 - ☀️ Q_1 is increased to $Q_1^2 = g_1(Q_1^1, Q_2^{1\omega})$.
 - ☀️ ...
- 🌐 This continues until we reach the fixpoint Q_1^ω .

A Better Run Sketch (cont.)

Summary of the calculation of $\mu Q_1.g_1(Q_1, \mu Q_2.g_2(Q_1, Q_2))$:

Q_1^0 $= \text{False}$	Q_2^{00} $= \text{False};$	Q_2^{01} $= g_2(Q_1^0, Q_2^{00});$	\dots	$Q_2^{0\omega}$
Q_1^1 $= g_1(Q_1^0, Q_2^{0\omega})$	Q_2^{10} $= Q_2^{0\omega};$	Q_2^{11} $= g_2(Q_1^1, Q_2^{10});$	\dots	$Q_2^{1\omega}$
\vdots	\vdots			
$Q_1^{\omega-2}$ $= g_1(Q_1^{\omega-3}, Q_2^{(\omega-3)\omega})$	$Q_2^{(\omega-2)0}$ $= Q_2^{(\omega-3)\omega};$	$Q_2^{(\omega-2)1}$ $= g_2(Q_1^{(\omega-2)}, Q_2^{(\omega-2)0});$	\dots	$Q_2^{(\omega-2)\omega}$
$Q_1^{\omega-1}$ $= g_1(Q_1^{\omega-2}, Q_2^{(\omega-2)\omega})$	$Q_2^{(\omega-1)0}$ $= Q_2^{(\omega-2)\omega};$	$Q_2^{(\omega-1)1}$ $= g_2(Q_1^{(\omega-1)}, Q_2^{(\omega-1)0});$	\dots	$Q_2^{(\omega-1)\omega}$
Q_1^ω $= g_1(Q_1^{\omega-1}, Q_2^{(\omega-1)\omega})$				

$Q_2^{0\omega} = g_2(Q_1^0, Q_2^{0\omega}) \subseteq g_2(Q_1^1, Q_2^{0\omega})$

$Q_2^{0\omega} = \mu Q_2.g_2(Q_1^0, Q_2) \subseteq \mu Q_2.g_2(Q_1^1, Q_2) = Q_2^{1\omega}$

Emerson-Lei Algorithm

```
1  function EL-Eval( $f$ ,  $e$ )  
  
2  if  $f = p$  then return  $\{s \mid p \in L(s)\}$ ;  
3  if  $f = Q$  then return  $e(Q)$ ;  
4  if  $f = g_1 \wedge g_2$  then  
5      return  $\text{EL-Eval}(g_1, e) \cap \text{EL-Eval}(g_2, e)$ ;  
6  if  $f = g_1 \vee g_2$  then  
7      return  $\text{EL-Eval}(g_1, e) \cup \text{EL-Eval}(g_2, e)$ ;  
8  if  $f = \langle a \rangle g$  then  
9      return  $\{s \mid \exists t (s \xrightarrow{a} t \text{ and } t \in \text{EL-Eval}(g, e))\}$ ;  
10 if  $f = [a]g$  then  
11     return  $\{s \mid \forall t (s \xrightarrow{a} t \text{ implies } t \in \text{EL-Eval}(g, e))\}$ ;  
12 if  $f = \mu Q_i.g(Q_i)$  then return  $\text{EL-Lfp}(g, e, Q_i)$ ;  
13 if  $f = \nu Q_i.g(Q_i)$  then return  $\text{EL-Gfp}(g, e, Q_i)$ ;  
14 end function
```

Emerson-Lei Algorithm (cont.)

- 🌐 The algorithm uses an array $A[1..N]$ to store the approximations to the fixpoints.
- 🌐 Initially, $A[i]$ is set to *False* if the i^{th} fixpoint formula is a least fixpoint and to *True* otherwise.
- 🌐 The approximation values $A[i]$ are not reset when evaluating the subformula $\mu Q_i . g(Q_i)$ or $\nu Q_i . g(Q_i)$.

Emerson-Lei Lfp

```
1  function EL-Lfp( $g, e, Q_i$ )
2  forall top-level greatest fixpoint subformulae  $\nu Q_j.g'(Q_j)$  of  $g$ 
3      do  $A[j] \leftarrow True$ ;
4  repeat
5       $Q_{old} \leftarrow A[i]$ ;
6       $A[i] \leftarrow EL-Eval(g, e[Q_i \leftarrow A[i]])$ ;
7  until  $A[i] = Q_{old}$ 
8  return  $A[i]$ ;
9  end function
```

Emerson-Lei Gfp

```
1  function EL-Gfp( $g, e, Q_i$ )
2  forall top-level least fixpoint subformulae  $\mu Q_j.g'(Q_j)$  of  $g$ 
3    do  $A[j] \leftarrow False$ ;
4  repeat
5     $Q_{old} \leftarrow A[i]$ ;
6     $A[i] \leftarrow EL-Eval(g, e[Q_i \leftarrow A[i]])$ ;
7  until  $A[i] = Q_{old}$ 
8  return  $A[i]$ ;
9  end function
```


Complexity Analysis

- 🌐 In the naive algorithm, the innermost fixpoint requires $O(n^k)$ iterations, where k is the maximum nesting depth of fixpoint operators.
- 🌐 The number of iterations of Emerson-Lei algorithm is $O((|f| \cdot n)^d)$.
 - ☀️ $|f|$ is an upper bound on the number of consecutive fixpoints of the same type in f .
 - ☀️ The number of iterations for each such sequence is $O(|f| \cdot n)$, each fixpoint requiring at most n iterations.
 - ☀️ With d alternating sequences, we have $O((|f| \cdot n)^d)$ iterations.

Representing Formulae Using OBDDs

- 🌐 The domain S is encoded by the vector \vec{x} .
- 🌐 Each atomic proposition p has an OBDD associated with it, denoted $OBDD_p(\vec{x})$.
 - ☀️ $\vec{y} \in \{0, 1\}^n$ satisfies $OBDD_p$ iff $p \in L(\vec{y})$.
- 🌐 Each transition a has an OBDD associated with it, denoted $OBDD_a(\vec{x}, \vec{x}')$.
 - ☀️ $(\vec{y}, \vec{z}) \in \{0, 1\}^{2n}$ satisfies $OBDD_a$ iff $(\vec{y}, \vec{z}) \in a$.
- 🌐 The environment is represented by a function $assoc$; $assoc[Q_i]$ gives the OBDD corresponding to the set of states associated with Q_i .
- 🌐 $assoc\langle Q \leftarrow B_Q \rangle$ creates a new association by associating an OBDD B_Q with Q .

🌐 The procedure B given below takes a μ -calculus formula f and an association list $assoc$ and returns an OBDD corresponding to the semantics of f .

- ☀ $B(p, assoc) = OBDD_p(\vec{x})$
- ☀ $B(Q_i, assoc) = assoc[Q_i]$
- ☀ $B(\neg f, assoc) = \neg B(f, assoc)$
- ☀ $B(f \wedge g, assoc) = B(f, assoc) \wedge B(g, assoc)$
- ☀ $B(f \vee g, assoc) = B(f, assoc) \vee B(g, assoc)$
- ☀ $B(\langle a \rangle f, assoc) = \exists \vec{x}' (OBDD_a(\vec{x}, \vec{x}') \wedge B(f, assoc)(\vec{x}'))$
- ☀ $B([a]f, assoc) = B(\neg \langle a \rangle \neg f, assoc)$
- ☀ $B(\mu Q.f, assoc) = \text{FIX}(f, assoc, OBDD_{False})$
- ☀ $B(\nu Q.f, assoc) = \text{FIX}(f, assoc, OBDD_{True})$

```
1  function FIX( $f$ ,  $assoc$ ,  $B_Q$ )
2   $bdd_{result} \leftarrow B_Q$ ;
3  repeat
4     $bdd_{old} \leftarrow bdd_{result}$ ;
5     $bdd_{result} \leftarrow B(f, assoc \langle Q \leftarrow bdd_{old} \rangle)$ ;
6  until  $equal(bdd_{old}, bdd_{result})$ 
7  return  $bdd_{result}$ ;
8  end function
```

An example

- Let the state space S be encoded by n boolean variables x_1, x_2, \dots, x_n .
- Let $OBDD_q(\vec{x})$ be the interpretation for q .
- The $OBDD$ corresponding to the transition a is $OBDD_a(\vec{x}, \vec{x}')$.
- Given an association list $assoc$ that pairs the $OBDD$ $B_Y(\vec{x})$ with Y .
- Consider the following formula:

$$f = \mu Z . ((q \wedge Y) \vee \langle a \rangle Z)$$

An example (cont.)

- 🌐 In the execution of `FIX`, bdd_{result} is initially set to:

$$N^0(\vec{x}) = OBDD_{False}.$$

- 🌐 At the end of the i -th iteration, the value of bdd_{result} is given by:

$$N^{i+1}(\vec{x}) = (OBDD_q(\vec{x}) \wedge B_Y(\vec{x})) \vee \exists \vec{x}' (OBDD_a(\vec{x}, \vec{x}') \wedge N^i(\vec{x}')).$$

- 🌐 The iteration stops when $N^i(\vec{x}) = N^{i+1}(\vec{x})$.

Translating CTL into the μ -Calculus

- 🌐 Consider systems with just one transition a .
- 🌐 The algorithm Tr takes as its input a CTL formula and outputs an equivalent μ -calculus formula:
 - ☀ $\text{Tr}(p) = p$
 - ☀ $\text{Tr}(\neg f) = \neg \text{Tr}(f)$
 - ☀ $\text{Tr}(f \wedge g) = \text{Tr}(f) \wedge \text{Tr}(g)$
 - ☀ $\text{Tr}(\mathbf{E}X f) = \langle a \rangle \text{Tr}(f)$
 - ☀ $\text{Tr}(\mathbf{E}[f \mathbf{U} g]) = \mu Y.(\text{Tr}(g) \vee (\text{Tr}(f) \wedge \langle a \rangle Y))$
 - ☀ $\text{Tr}(\mathbf{E}G f) = \nu Y.(\text{Tr}(f) \wedge \langle a \rangle Y)$

🌐 Example:

$$\begin{aligned} & \text{Tr}(\mathbf{EG} \mathbf{E}[p \mathbf{U} q]) \\ &= \nu Y.(\text{Tr}(\mathbf{E}[p \mathbf{U} q]) \wedge \langle a \rangle Y) \\ &= \nu Y.(\mu Z.(q \vee (p \wedge \langle a \rangle Z)) \wedge \langle a \rangle Y) \end{aligned}$$

- 🌐 Any resulting μ -calculus formula is closed.
- 🌐 We can omit the environment e from the translation.

NP and co-NP

- 🌐 We will see model checking μ -calculus is in $\text{NP} \cap \text{co-NP}$.
- 🌐 A language L is in NP if there exists a polynomial-time nondeterministic algorithm M such that:
 - ☀ if $x \in L$, then $M(x) = \text{"yes"}$ for some computation path, and
 - ☀ if $x \notin L$, then $M(x) = \text{"no"}$ for all computation paths.
- 🌐 A language L is in co-NP if there exists a polynomial-time nondeterministic algorithm M such that:
 - ☀ if $x \in L$, then $M(x) = \text{"yes"}$ for all computation paths, and
 - ☀ if $x \notin L$, then $M(x) = \text{"no"}$ for some computation path.
- 🌐 $\text{co-NP} = \{L \mid \bar{L} \in \text{NP}\}$.

Relations between P, NP, and co-NP

🌐 Current consensus (still open):

- ☀ $P \neq NP$
- ☀ $NP \neq \text{co-NP}$
- ☀ $P \neq NP \cap \text{co-NP}$

🌐 If an NP-complete problem is in co-NP, then $NP = \text{co-NP}$.

- ☀ Suppose L is an NP-complete problem that is also in co-NP.
- ☀ Let NTM M decide L .
- ☀ For any $L' \in NP$, there is a reduction R from L' to L .
- ☀ $L' \in \text{co-NP}$ as it is decided by NTM $M(R(\cdot))$.
- ☀ Hence $NP \subseteq \text{co-NP}$.
- ☀ The other direction $\text{co-NP} \subseteq NP$ is symmetric.

- 🌐 **Problem:** Given a finite model M , a state s , and a μ -calculus formula f , does $M, s \models f$?
- 🌐 Best known upper bound for this problem is $\text{NP} \cap \text{co-NP}$.

Model Checking μ -Calculus Is in NP

- 🌍 Consider the following nondeterministic algorithm:
 - ☀️ **Guess** the greatest fixpoints and **compute** the least fixpoints by iteration.
 - ☀️ The guess for a greatest fixpoint is **checked** to see that it really is a fixpoint.
 - ☀️ Finally, check if the resulting set contains the given state.
- 🌍 The greatest fixpoint must contain any verified guess.
- 🌍 By monotonicity, this nondeterministic algorithm computes a subset of the real interpretation of the formula.
- 🌍 There is a run of the algorithm which calculates the set of states satisfying the μ -calculus formula.
- 🌍 Consequently, the problem is in NP.

Model Checking μ -Calculus Is in co-NP

- 🌐 Recall that $\text{co-NP} = \{L \mid \bar{L} \in \text{NP}\}$.
- 🌐 Consider the following nondeterministic algorithm:
 - ☀️ Negate the input formula.
 - ☀️ Apply the algorithm on the previous slide.
- 🌐 Consequently, the problem is in co-NP.
- 🌐 Hence, the problem is in $\text{NP} \cap \text{co-NP}$.

Open Problem

- 🌐 **Open Problem:** Is there a polynomial model checking algorithm for the μ -calculus?
- 🌐 It is a long standing open problem.
- 🌐 Clarke *et al.* conjecture NO in the book.
- 🌐 If the problem was NP-complete, then $NP = co-NP$, which is believed to be unlikely.
- 🌐 This suggests that it would be very difficult to prove the conjecture.