Today’s Lecture

**Symbolic model checking with BDDs**

- **Symbolic**: manipulate sets (of states and transitions) rather than individual elements and represent sets as Boolean formulas.
- **Represent Boolean formulas as BDDs**
Today’s Lecture

• Symbolic model checking
  – Basics of symbolic representation
  – Quantified Boolean formulas (QBF)
  – Checking G p
  – Fixpoint theory
  – Checking CTL properties

Sets as Boolean functions

• Every finite set can be represented as a Boolean function
  – Suppose the set has N (> 0) elements
  – Each element is encoded as a string of at least ⌈ log M ⌉ bits, where M is the number of elements in the universe
  – Characteristic Boolean function is the one whose ON-set (satisfying assignments) are those strings
  – Empty set is “False”
Set Operations as Boolean Operations

- $A \cup B = ?$
- $A \cap B = ?$
- $A \subset B = ?$
- Is $A$ empty?

Sets of states and transitions

- Set of states $\rightarrow$ each state $s$ is bit-string comprising values of state variables
- Set of transitions $\rightarrow$
  - Transition is a state pair $(s, s')$
  - View the pair as a combined bit-string
- From now, we will view the set of states $S$ and the transition relation $R$ as Boolean formulas over vector of current state variables $v$ and next state variables $v'$
  - $S(v)$, $R(v, v')$
Quantified Boolean Formulas

- Let $F$ denote a Boolean formula, and $v$ denote one or more Boolean variables.
- A quantified Boolean formula $\phi$ is obtained as:
  \[ \phi ::= F \mid \exists v \phi \mid \forall v \phi \mid \phi \land \phi \mid \phi \lor \phi \mid \neg \phi \]
- How do you express $\exists v_i \phi$ and $\forall v_i \phi$ in terms of $\phi$’s cofactors and standard Boolean operators?

Symbolic Model Checking $G \varphi$

- Given: Set of initial states $S_0$, transition relation $R$.
- Check property $G \varphi$ (or $AG \varphi$).
- How symbolic model checking will do this:
  - Compute $S_0, S_1, S_2, \ldots$ where $S_i$ is the set of states reachable from some initial state in at most $i$ steps.
    - What kind of search is this: DFS or BFS?
    - When do we stop?
  - After computing each $S_i$, check whether any element of $S_i$ satisfies $\neg \varphi$ [How?]
    - How do we generate a counterexample?
Reachability Analysis

• The process of computing the set of states reachable from some initial state in 0 or more steps
  – Often characterized as checking (AG true)
  – The resulting set is called “reachable set” or “set of reachable states”
    • This is the “strongest invariant” of the system → WHY? What is a “system invariant”?

Implementing Reachability Analysis

• How is $S_i$ related to $S_{i+1}$?
  – In words
  – As a recurrence relation using QBF
Implementing Reachability Analysis

• How is $S_i$ related to $S_{i+1}$?
• $v \in S_{i+1}$ iff $v \in S_i$ or there is a state $x \in S_i$ such that $R(x, v)$
• $S_{i+1}(v) = S_i(v) \lor \exists x \{ S_i(x) \land R(x, v) \}$

- $F[x/y]$ means that we substitute $x$ for $y$ in $F$
Implementing Reachability Analysis

\[ i := 0; \]
\[ \text{do } \{ \]
\[ \quad i++; \]
\[ \quad S_i(v) = S_{i-1}(v) \lor (\exists v \{ S_{i-1}(v) \land R(v,v') \}) [v/v'] \]
\[ \} \text{ while } (S_i(v) \neq S_{i-1}(v)) \]
\[ S_i(v) \text{ is the set of reachable states} \]

BDD Issues

- Remember that \( S_i \) and \( R \) are represented as BDDs
- How large they grow determines the space and time usage of the algorithm
Backwards Reachability

• Suppose we want to verify $G \neg p$
• The formula $\neg p$ characterizes all error states
• We can search backwards for a path to an error state from some initial state
  – Compute $E_0$, $E_1$, $E_2$, ... as states reachable from the error states in at most 0, 1, 2, ... steps
    – $E_0 = \neg p$
    – How to express $E_{i+1}$ in terms of $E_i$?
• Why would we want to do backwards reachability analysis? Is it always better?

Verification of $G \neg p$

• Corresponding CTL formula is $AG \neg p$
• with Forward Reachability Analysis:
  – Check if some $S_i \land \neg p$ is true
• with Backward Reachability Analysis:
  – Set $E_0 = \neg p$
  – Check if $E_k \land S_0$ is true for any $k$
Symbolic Model Checking, General Case

- We will consider properties in CTL
  - As implemented in the original SMV model checker
  - Later we will see how LTL properties can be verified using symbolic techniques

Model Checking Arbitrary CTL

- Need only consider the following types of CTL properties:
  - $E X p$
  - $E G p$
  - $E ( p U q )$

- Why? $\iff$ all others are expressible using above
  - $A G p = ?$
  - $A G ( p \rightarrow ( A F q ) ) = ?$
Fixpoint Theory

- Theory about elements/points that are unchanged by application of a function (hence “fixed point”)
- A concept from mathematics and denotational semantics of programming languages
- For us: Theoretical concepts and results that will help us design algorithms for CTL model checking

Fixpoint (Fixed point)

- Let $\Sigma$ be a set (the “universe”), and $\Sigma' \subseteq \Sigma$
  - In model checking, $\Sigma = \text{True}$
- Let $\tau : P(\Sigma) \rightarrow P(\Sigma)$
  - $P(\Sigma)$ is the power set of $\Sigma$
- Definition: $\Sigma'$ is a fixpoint of $\tau$ if $\tau(\Sigma') = \Sigma'$
Example of Fixpoint

• Let
  – \( \Sigma = \{s_0, s_1\} \)
  – \( \tau(Z) = Z \cup \{s_0\}, \ Z \subseteq \Sigma \)

• What is a fixpoint of \( \tau \)? Is there only one?

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Model Checking Example

In the context of Reachability Analysis:

• What’s an example of a fixpoint we’ve seen already? What was \( \tau \)?

\[ \Sigma' \]
Model Checking Example

• What’s an example of a fixpoint we’ve seen already? What was $\tau$?
  – A G true can be computed using a fixpoint formulation
  – $\tau$ computes the “next state”
• What we need: a way to generalize this for arbitrary CTL properties: EX, EG, EU
  – Fixpoint theory helps us do this

More Definitions

• $\tau$ is **monotonic** if for $P \subseteq Q$, $\tau(P) \subseteq \tau(Q)$
• $\tau$ is **$\cup$-continuous** if: $P_1 \subseteq P_2 \subseteq P_3 \ldots \Rightarrow \tau(\bigcup_i P_i) = \bigcup_i \tau(P_i)$
• $\tau$ is **$\cap$-continuous** if: $P_1 \supseteq P_2 \supseteq P_3 \ldots \Rightarrow \tau(\bigcap_i P_i) = \bigcap_i \tau(P_i)$
Main Theorems (Tarski)

• \( \tau \) is **monotonic** if for \( P \subseteq Q, \tau(P) \subseteq \tau(Q) \)
• \( \tau \) is **\( \cup \)-continuous** if: \( P_1 \subseteq P_2 \subseteq P_3 \ldots \Rightarrow \tau(\cup_i P_i) = \cup_i \tau(P_i) \)
• \( \tau \) is **\( \cap \)-continuous** if: \( P_1 \supseteq P_2 \supseteq P_3 \ldots \Rightarrow \tau(\cap_i P_i) = \cap_i \tau(P_i) \)

• A monotonic \( \tau \) on \( P(\Sigma) \) always has
  - a **least fixpoint**: written \( \mu Z. \tau(Z) \)
  - a **greatest fixpoint**: written \( \nu Z. \tau(Z) \)
  - least and greatest refer to the size of the fixpoint \( Z \).

Least and Greatest Fixpoints

• Let
  - \( \Sigma = \{s_0, s_1\} \)
  - \( \tau(Z) = Z \cup \{s_0\}, \ Z \subseteq \Sigma \)

• What is the least fixpoint of \( \tau \)? The greatest fixpoint? Are they the same?
Main Theorems (Tarski)

- \( \tau \) is monotonic if for \( P \subseteq Q \), \( \tau(P) \subseteq \tau(Q) \)
- \( \tau \) is \( \cup \)-continuous if: \( P_1 \subseteq P_2 \subseteq P_3 \ldots \Rightarrow \tau(\bigcup_i P_i) = \bigcup_i \tau(P_i) \)
- \( \tau \) is \( \cap \)-continuous if: \( P_1 \supseteq P_2 \supseteq P_3 \ldots \Rightarrow \tau(\bigcap_i P_i) = \bigcap_i \tau(P_i) \)

- A monotonic \( \tau \) on \( P(\Sigma) \) always has
  - a least fixpoint: written \( \mu Z. \ \tau(Z) \)
  - a greatest fixpoint: written \( \nu Z. \ \tau(Z) \)
  - \( \mu Z. \ \tau(Z) = \bigcap \{ Z \mid \tau(Z) \subseteq Z \} \)
  - \( \nu Z. \ \tau(Z) = \bigcup \{ Z \mid \tau(Z) \supseteq Z \} \)

Main Theorems (Tarski)

- \( \tau \) is monotonic if for \( P \subseteq Q \), \( \tau(P) \subseteq \tau(Q) \)
- \( \tau \) is \( \cup \)-continuous if: \( P_1 \subseteq P_2 \subseteq P_3 \ldots \Rightarrow \tau(\bigcup_i P_i) = \bigcup_i \tau(P_i) \)
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- A monotonic \( \tau \) on \( P(\Sigma) \) always has
  - a least fixpoint: written \( \mu Z. \ \tau(Z) \)
  - a greatest fixpoint: written \( \nu Z. \ \tau(Z) \)
  - \( \mu Z. \ \tau(Z) = \bigcap \{ Z \mid \tau(Z) \subseteq Z \} \)
  - \( \nu Z. \ \tau(Z) = \bigcup \{ Z \mid \tau(Z) \supseteq Z \} \)
  - \( \mu Z. \ \tau(Z) = \bigcup_i \tau^i(\phi) \) when \( \tau \) is \( \cup \)-continuous
  - \( \nu Z. \ \tau(Z) = \bigcap_i \tau^i(\Sigma) \) when \( \tau \) is \( \cap \)-continuous
Main Lemma for us

- If $\Sigma$ is finite and $\tau$ is monotonic, then $\tau$ is also $\cup$-continuous and $\cap$-continuous
- Proof? (of $\cup$-continuous)
  $\tau$ is $\cup$-continuous if: $P_1 \subseteq P_2 \subseteq P_3 \ldots \Rightarrow \tau(\cup_i P_i) = \cup_i \tau(P_i)$

What’s Left?

- We have the needed fixpoint theory
- Now all we need to do is formulate the result of CTL operators as fixpoints
  - We will identify a CTL formula with the set of states that satisfy that formula
    - Remember that CTL formulas start with A or E which are interpreted over states, not runs
CTL Results as Fixpoints

• $A G p = \forall Z. p \land AX Z$
  – $\tau(Z) = p \land AX Z$
  – Given a point (state) in $Z$, $\tau$ maps it to another state that
    • Satisfies $p$
    • Can reach a state in $Z$ along any execution path in one step
    • So what happens when we reach $\tau$'s fixpoint?
  – Remember: $\forall$ fixpoint computation starts with the universal set $\Sigma$ and works ‘downward’

Other Fixpoint Formulations

• $EF p = \mu Z. p \lor EX Z$
• $EG p = \forall Z. p \land EX Z$
• $E(p U q) = \mu Z. q \lor (p \land EX Z)$

• Intuitively:
  – Eventualities $\rightarrow$ least fixpoints
  – Always/Forever $\rightarrow$ greatest fixpoints
Model Checking CTL Properties

• We define a general recursive procedure called “Check” to do the fixpoint computations

• Definition of Check:
  – Input: A CTL property $\Pi$ (and implicitly, $R$)
  – Output: A Boolean formula $B$ representing the set of states satisfying $\Pi$

• If $S_0(v) \implies B(v)$, then $\Pi$ is true

The “Check” procedure

Cases:
• If $\Pi$ is a Boolean formula, then $\text{Check}(\Pi) = \Pi$
• Else:
  – $\Pi = \text{EX} \, p$, then $\text{Check}(\Pi) = \text{CheckEX}(\text{Check}(p))$
  – $\Pi = \text{E}(p \text{ U } q)$, then
    $\text{Check}(\Pi) = \text{CheckEU}(\text{Check}(p), \text{Check}(q))$
  – $\Pi = \text{E} \, \text{G} \, p$, then $\text{Check}(\Pi) = \text{CheckEG}(\text{Check}(p))$

• Note: What are the arguments to $\text{CheckEX}$, $\text{CheckEU}$, $\text{CheckEG}$? CTL properties or Boolean formulas?
CheckEX

• CheckEX(p) returns a set of states such that p is true in their next states

• How to write this?

\[ \exists x \ [ p(x) \cdot R(s, x) ] \]

CheckEU

• CheckEU(p, q) returns a set of states, each of which is such that
  – Either q is true in that state
  – Or p is true in that state and you can get from it to a state in which p U q is true
CheckEU

• CheckEU(p, q) returns a set of states, each of which is such that
  – Either q is true in that state
  – Or p is true in that state and you can get from it to a state in which p U q is true

• Let Z₀ be our initial approximation to the answer to CheckEU(p, q)

• \( Z_k(v) = \{ q(v) + [ p(v) \cdot \exists v' \{ R(v, v') \cdot Z_{k-1}(v') \} ] \} \)

• What’s Z₀? Why will this terminate?

Summary

• EGp computed similarly

• Definition of Check:
  – Input: A CTL property \( \Pi \) (and implicitly, R)
  – Output: A Boolean formula B representing the set of states satisfying \( \Pi \)

• All Boolean formulas represented “symbolically” as BDDs
  – “Symbolic Model Checking”
Counterexample/Witness Generation for CTL

• Counterexample = run showing how the property is violated
  – Formulas with universal path quantifier $A$
• Witness = run showing how the property is satisfied
  – Formulas with existential path quantifier $E$
  – Can also view as counterexample for the negated property
    • E.g. $E \ G p$ and $A \ F \neg p$

Witness Generation for $EG \ p$

• Fixpoint formulation for $E \ G \ p$:
  – $\forall Z. p \land EX Z$
  – $\tau(Z) = p \land EX Z$
• Fixpoint computation yields sequence $Z_0, Z_1, \ldots, Z_k$
  – $Z_0 = \text{True}$ (universal set)
  – $Z_1 = \tau(\text{True}) = ?$
  – each $Z_i$ is a BDD representing a set of states
  – How would you describe an element of $Z_i$ ?
• We need to generate the counterexample from $S_0, R, Z_0, Z_1, \ldots, Z_k$
Witness Generation for EG p

- Fixpoint computation yields sequence $Z_0, Z_1, \ldots, Z_k$
  - A state in $Z_i$ ($i > 0$) satisfies $p$ and there is a path of length $i-1$ from that state comprising states satisfying $p$
  - How would you describe an element of $Z_k$?
    - Remember: it’s the fixpoint

Witness Generation for EG p

- Fixpoint computation yields sequence $Z_0, Z_1, \ldots, Z_k$
  - A state in $Z_i$ satisfies $p$ and there is a path of length $i-1$ from that state comprising states satisfying $p$
  - How would you describe an element of $Z_k$?
    - State in $Z_k$ has path from it of length $k-1$ or more (including a cycle) with all states satisfying $p$
    - If $S_0$ is contained in $Z_k$, any initial state has such a path
Witness Generation for EG $p$

- Let $s_0$ be an initial state with a desired witness path
  - We need to reproduce one such witness
  - How can we do this?

- Main insight: desired successor of $s_0$ also satisfies EG $p$, and so on
- Look for a cycle in such a computed chain
  - Why should there be a cycle?
Fairness

• A computation path is defined as fair if a fairness constraint \( p \) is true infinitely often along that path
  – Fairness constraint is a state predicate
  – Generalized to set of fairness constraints \( \{p_1, p_2, \ldots, p_k\} \) by requiring each element of the subset to be true infinitely often

• Example: Every process in an asynchronous composition must be scheduled infinitely often