Property Specifications –Lecture 1

Jim Browne

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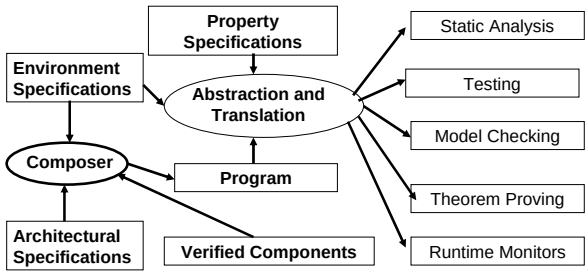
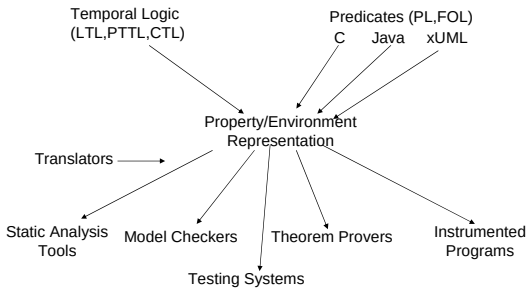
Multi-Targeted Specifications



Property Specification and Evaluation



- Properties = Knowledge of Component/System Behavior
  - A property can usually be defined as a state machine.
  - Properties are always defined with respect to an environment for the component/system.
- Environment = Set of properties which generates a closed system for execution or verification of a component or system.
  - Environments should be specifiable as set of properties for an executable entity

What Types Properties Should Be Specifiable?

Pre-Condition/Post-Condition pairs for units with identifiable semantics.

Occurrence or non-occurrence of specific states or events.

Sequences of states/events/operations which can or cannot occur => paths.

Security properties => information flow and access control.

Performance properties => time to execute a given path, etc.

Representation Issues

1. Syntax should be consistent with programming system for components/systems
2. Language should provide a library of templates for commonly occurring properties.
3. Language should support extending the library of templates.
4. Language should practice separation of concerns.

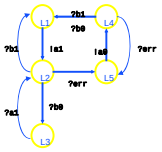
Pre-Condition => Post-Condition

Specify some subset of the state of the system before the execution of a component and some subset of the state after the execution of a component.

Pre-Condition => Post-Condition pairs can be specified in temporal logics

Input/Output Relation is an example of a pre-condition => post-condition

Reasoning about Executions



Conceptual View

Explored State-Space (computation tree)

[L1, (mt1, vr1), ….]

[L2, (mt2, vr2), ….]

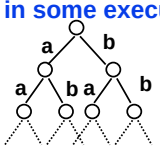
[L3, (mt3, vr3), ….] [L5, (mt5, vr5), ….]

- We want to reason about execution trees
  - > tree node = snap shot of the program's state
- Reasoning consists of two layers
  - > defining predicates on the program states (control points, variable values)
  - > expressing temporal relationships between those predicates

Branching Time Logic

- Branching time logic views a computation as a (possibly infinite) tree or dag of states connected by atomic events
- At each state the outgoing arcs represent the actions leading to the possible next states in some execution
- Example:

$P = (a \rightarrow P) \sqcap (b \rightarrow P)$



Notation

- Variant of branching time logic that we will look at is called CTL*, for Computational Tree Logic (star)
- In this logic
  - A = "for every path"
  - E = "there exists a path"
  - G = “globally” (similar to $\Box$)
  - F = “future” (similar to $\Diamond$)

Paths versus States

- A & E refer to paths
  - A requires that all paths have some property
  - E requires that at least some path has the property
- G & F refer to states on a path
  - G requires that all states on the given path have some property
  - F requires that at least one state on the path has the property

Examples

- AG p
  - For every computation (i.e., path from the root), in every state, p is true
  - Hence, means the same as $\Box$ p
- EG p
  - There exists a computation (path) for which p is always true
  - Note, unlike LTL not all executions need have this property

Examples

- AF p
  - For every path, eventually state p is true
  - Hence, means the same as ◊ p
  - Therefore, p is *inevitable*
- EF p
  - There is some path for which p is eventually true
  - I.e. p is "reachable"
  - Therefore, p will hold *potentially*

More Examples

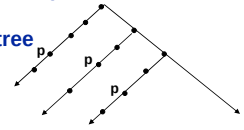
- EFAG p
  - For some computation (E), there is a state (F), such that for all paths from that state (A), globally (G) p is true
- AGEF halt
  - For all computations (A), and for all states in it (G), there is a path (E) along which eventually (F) halt occurs
- EGEF p
  - For some computation (E), for all states in that computation (G), there is a path (E) in which p is eventually (F) true

Other Operators for States

- Can also have next and until
  - represented as X and U respectively
  - AX p means that for all next states, p will hold
  - E[p U q] means that for some path there is a state where q holds and p holds in all states up to that state

More Examples

- Show that EGEF p is the same as EGF p or provide a counter example to illustrate why not
  - EGEF p means that there is a path such that from all states, there is a path such that p is eventually true
  - EGF p means that there is a path such that from all states, p is eventually true in that path
  - Consider the following tree
    - First one is true
    - Second one is not

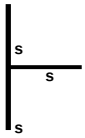


CTL

- In some versions the symbols are required to occur in pairs of the form
  - > AG, AF, EG, EF
  - > Called CTL (no star)
  - > Important restriction for tools such as model checkers

Traffic Controller

- Consider a traffic controller on a north-south highway with a road off to the east



- Each road has a sensor that goes to true when a car crosses it
- For simplicity, no north or south bound car will turn

Traffic Controller

- To reason about them, we name the sensors
  - > N (north)
  - > S (south)
  - > E (east)
- We also name the output signals at each end of the intersection
  - > N-go (cars from the north can go)
  - > S-go (cars from the south can go)
  - > E-go (cars from the east can go)

Safety Property

- If cars from the east have a go-signal, then no other car can have a go-signal

$$AG \neg (E\text{-}go \wedge (N\text{-}go \vee S\text{-}go))$$

Liveness properties

- If a sensor registers a car, then the car will be able to go through the intersection

$$AG\ (\neg\ N\text{-}go \wedge N \rightarrow AF\ N\text{-}go)$$
$$AG\ (\neg\ S\text{-}go \wedge S \rightarrow AF\ S\text{-}go)$$
$$AG\ (\neg\ E\text{-}go \wedge E \rightarrow AF\ E\text{-}go)$$

- If the above are true, then the controller is free of deadlock

Efficiency

- Since north and south bound cars can safely pass by each other we can state a possibility

$$EF\ (N\text{-}go \wedge S\text{-}go)$$

Fairness

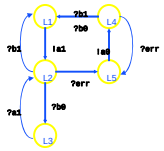
- We can't have a car stop in the intersection

$$AG\ \neg\ (N\text{-}go \wedge N)$$
$$AG\ \neg\ (S\text{-}go \wedge S)$$
$$AG\ \neg\ (E\text{-}go \wedge E)$$

Yet More Temporal Logics

- The logic we've used so far is concerned with instances of state
  - > assertions about a future state(s)
  - > predicate is applied to each selected state
- What about contiguous collections of states?
- Interval temporal logic
  - > assertions over intervals of time
  - > have to worry about overlapping intervals

Reasoning about Executions



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Computational Tree Logic (CTL)

Syntax

```
Φ ::=  P                                  …primitive propositions
     | !Φ  | Φ && Φ | Φ || Φ | Φ -> Φ      …propositional connectives
     | AG Φ | EG Φ | AF Φ | EF Φ           …temporal operators
     | AX Φ | EX Φ | A[Φ U Φ] | E[Φ U Φ]
```

Semantic Intuition

path quantifier

temporal operator

AG p …along *All* paths p holds *Globally*

EG p …there *Exists* a path where p holds *Globally*

AF p …along *All* paths p holds at some state in the *Future*

EF p …there *Exists* a path where p holds at some state in the *Future*

Computational Tree Logic (CTL)

Syntax

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Φ ::=  P                                  …primitive propositions
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     | AG Φ | EG Φ | AF Φ | EF Φ           …path/temporal operators
     | AX Φ | EX Φ | A[Φ U Φ] | E[Φ U Φ]
```

Semantic Intuition

AX p …along *All* paths, p holds in the *neXt* state

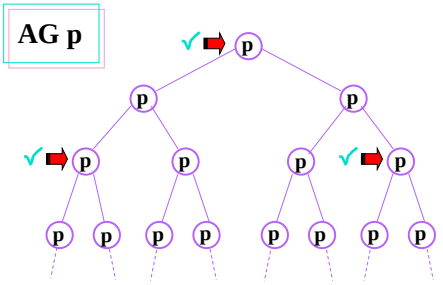
EX p …there *Exists* a path where p holds in the *neXt* state

A[p U q] …along *All* paths, p holds *Until* q holds

E[p U q] …there *Exists* a path where p holds *Until* q holds

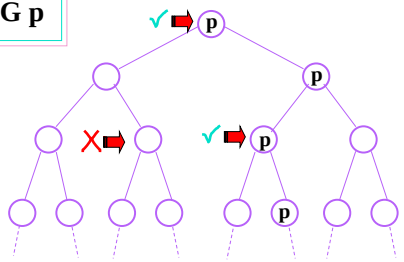
Computation Tree Logic

AG p



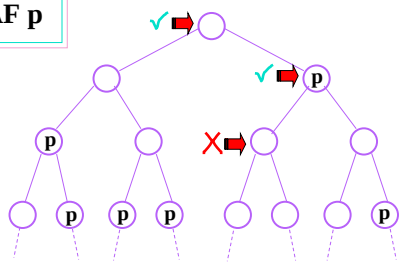
Computation Tree Logic

EG p



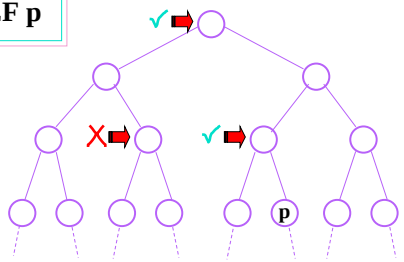
Computation Tree Logic

AF p



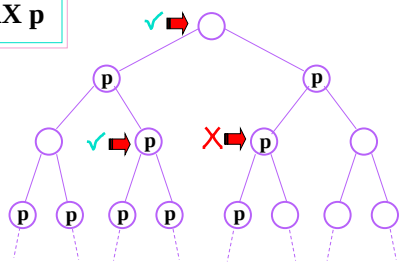
Computation Tree Logic

EF p



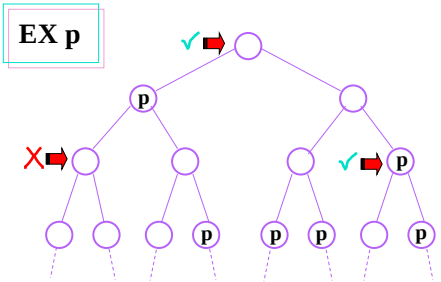
Computation Tree Logic

AX p



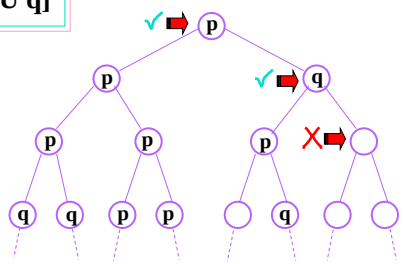
Computation Tree Logic

EX p



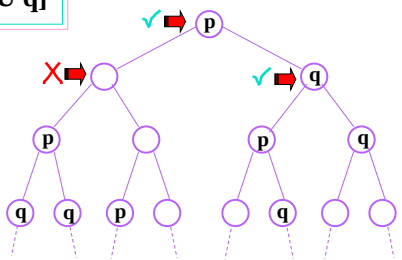
Computation Tree Logic

A[p U q]



Computation Tree Logic

E[p U q]



Example CTL Specifications

- For any state, a request (for some resource) will eventually be acknowledged

  AG(requested -> AF acknowledged)

- From any state, it is possible to get to a restart state

  AG(EF restart)

- An upwards travelling elevator at the second floor does not changes its direction when it has passengers waiting to go to the fifth floor

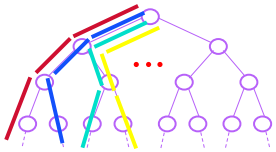
  AG((floor=2 && direction=up && button5pressed) -> A[direction=up U floor=5])

CTL Notes

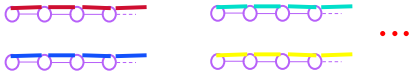
- Invented by E. Clarke and E. A. Emerson (early 1980's)
- Specification language for Symbolic Model Verifier (SMV) model-checker
- SMV is a *symbolic* model-checker instead of an *explicit-state* model-checker
- Symbolic model-checking uses Binary Decision Diagrams (BDDs) to represent boolean functions (both transition system and specification

Linear Temporal Logic

Restrict path quantification to *"ALL" (no "EXISTS")*



Reason in terms of linear *traces* instead of branching *trees*



Linear Temporal Logic (LTL)

Syntax

```
Φ ::=  P                                    …primitive propositions
     | !Φ  | Φ && Φ | Φ || Φ | Φ -> Φ  …propositional connectives
     | []Φ | <>Φ     | Φ U Φ   | X Φ       …temporal operators
```

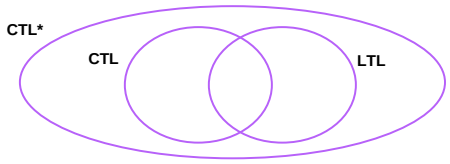
Semantic Intuition

[]Φ	*…always* **Φ**	
<>Φ	*…eventually* **Φ**	
Φ U Γ	*…***Φ** *until* **Γ**	

LTL Notes

- Invented by Prior (1960's), and first use to reason about concurrent systems by A. Pnueli, Z. Manna, etc.
- LTL model-checkers are usually explicit-state checkers due to connection between LTL and automata theory
- Most popular LTL-based checker is Spin (G. Holzman)

Comparing LTL and CTL



- CTL is not strictly more expression than LTL (and vice versa)
- CTL* invented by Emerson and Halpern in 1986 to unify CTL and LTL
- We believe that almost all properties that one wants to express about software lie in intersection of LTL and CTL

Motivation for Specification Patterns

- Temporal properties are not always easy to write
- Clearly many specifications can be captured in both CTL and LTL

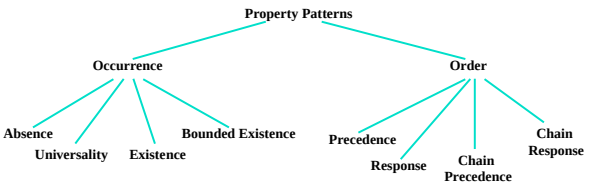
Example: **action Q must respond to action P**

CTL: `AG(P -> AF Q)` LTL: `[](P -> <>Q)`

We use specification patterns to:

- Capure the experience base of expert designers
- Transfer that experience between practictioners.

Pattern Hierarchy



Classification

- *Occurrence* Patterns:
  - > require states/events to occur or not to occur
- *Order* Patterns
  - > constrain the order of states/events

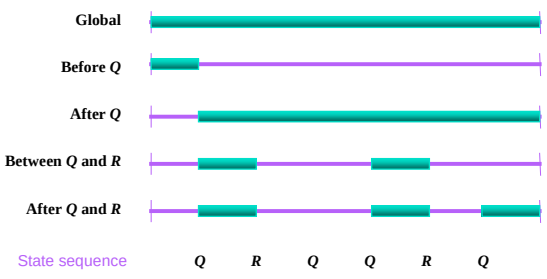
Occurrence Patterns

- Absence: A given state/event does not occur within a scope
- Existence: A given state/event must occur within a scope
- Bounded Existence: A given state/event must occur *k* times within a scope
  - > variants: *at least k* times in scope, *at most k* times in scope
- Universality: A given state/event must occur throughout a scope

Order Patterns

- Precedence: A state/event P must always be preceded by a state/event Q within a scope
- Response: A state/event P must always be followed a state/event Q within a scope
- Chain Precedence: A sequence of state/events P1, …, Pn must always be preceded by a sequence of states/events Q1, …, Qm within a scope
- Chain Response: A sequence of state/events P1, …, Pn must always be followed by a sequence of states/events Q1, …, Qm within a scope

Pattern Scopes



The Response Pattern

Intent

To describe cause-effect relationships between a pair of events/states. An occurrence of the first, the cause, must be followed by an occurrence of the second, the effect. Also known as **Follows** and **Leads-to**.

Mappings: *In these mappings, **P** is the cause and **S** is the effect*

LTL:

Globally:	`[](P -> <>S)`
Before R:	`<>R -> (P -> (!R U (S & !R))) U R`
After Q:	`[](Q -> [](P -> <>S))`
Between Q and R:	`[]((Q & !R & <>R) -> (P -> (!R U (S & !R))) U R)`
After Q until R:	`[](Q & !R -> ((P -> (!R U (S & !R))) W R)`

The Response Pattern (continued)

Mappings: *In these mappings, **P** is the cause and **S** is the effect*

CTL:

Globally:	`AG(P -> AF(S))`
Before R:	`A[((P -> A[!R U (S & !R)]) | AG(!R)) W R]`
After Q:	`A[!Q W (Q & AG(P -> AF(S))]`
Between Q and R:	`AG(Q & !R -> A[((P -> A[!R U (S & !R)]) | AG(!R)) W R])`
After Q until R:	`AG(Q & !R -> A[(P -> A[!R U (S & !R)]) W R])`

Examples and Known Uses:

Response properties occur quite commonly in specifications of concurrent systems. Perhaps the most common example is in describing a requirement that a resource must be granted after it is requested.

Relationships

Note that a Response property is like a converse of a Precedence property. Precedence says that some cause precedes each effect, and...

Specify Patterns in Bandera

The Bandera Pattern Library is populated by writing pattern macros:

```
pattern {
   name = “Response”
   scope = “Globally”
   parameters = {P, S}
   format = “{P} leads to {S} globally”
   ltl = “[]({P} –> <>{S})”
   ctl = “AG({P} –> AF({S}))”
}
```


Evaluation

- 555 TL specs collected from at least 35 different sources
- 511 (92%) matched one of the patterns
- Of the matches...
  - > Response: 245 (48%)
  - > Universality: 119 (23%)
  - > Absence: 85 (17%)

Questions

- Do patterns facilitate the learning of specification formalisms like CTL and LTL?
- Do patterns allow specifications to be written more quickly?
- Are the specifications generated from patterns more likely to be correct?
- Does the use of the pattern system lead people to write more expressive specifications?

Based on anecdotal evidence, we believe the answer to each of these questions is “yes”

For more information...

- Pattern web pages and papers

  http://www.cis.ksu.edu/santos/spec-patterns