

Computation Tree Logic

Luis Tertulino & Ronaldo Silveira

October 22, 2015

- 1 In previous chapters...
- 2 Introduction
- 3 How to communicate
 - Syntax of CTL
 - Semantics of CTL
- 4 Some examples of what we can say
- 5 More about semantics
 - Equivalences
- 6 Improving our language

Previously on Temporal Logic Week...

Temporal Logic

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- A brief introduction to Propositional Logic, its syntax and its semantics

Previously on Temporal Logic Week...

Temporal Logic

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- A brief introduction to Propositional Logic, its syntax and its semantics
- Formal models of time

Previously on Temporal Logic Week...

Temporal Logic

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- A brief introduction to Propositional Logic, its syntax and its semantics
- Formal models of time
 - Frames and Flows of time

Previously on Temporal Logic Week...

Temporal Logic

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- A brief introduction to Propositional Logic, its syntax and its semantics
- Formal models of time
 - Frames and Flows of time
- Temporal Logic extends the Propositional Logic
 - The connectives H and G

Previously on Temporal Logic Week...

Temporal Logic

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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- Formal models of time
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 - The connectives H and G
- Some practical applications

Motivation

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- Needing of uncertainty;

Motivation

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- Needing of uncertainty;
- Different paths of the future;

Intuition

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

In Computation Tree Logic (CTL) the model of time is a tree-like structure. This way, we cannot use Linear Temporal Logic (LTL) to express the existence of a certain path of time in which some event occurs.

History

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

CTL was defined by:



Figure 1:
Mordechai Ben-Ari



Figure 2: Amir
Pnueli



Figure 3: Zohar
Manna

History

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

And, at the same time by:



Figure 4: Ernest
Allen Emerson



Figure 5: Edmund
Clarke

Syntax

Definition

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

The syntax of CTL consists on the syntax of temporal logic plus some path operators. The class of formulas can be defined in Backus-Naur form. If ϕ is a formula:

Syntax

Definition

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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$$\phi ::= \perp \mid \top \mid p \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \phi \rightarrow \phi \mid AX\phi \mid EX\phi \mid$$

$$AF\phi \mid EF\phi \mid AG\phi \mid EG\phi \mid A[\phi U\phi] \mid E[\phi U\phi]$$

Syntax

Definition

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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$$AF\phi \mid EF\phi \mid AG\phi \mid EG\phi \mid A[\phi U\phi] \mid E[\phi U\phi]$$

With p as a literal (atomic formula), AX , EX , AF , EF , AG e EG unary operators.

Syntax Intuition

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

The propositional operators: $\neg, \vee, \wedge, \rightarrow$ have the same meaning of in the propositional logic.

Syntax

Intuition

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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The path-specific operators can be read as:

Syntax

Intuition

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silva

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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The temporal operators, as in LTL, can be read as:

- X : “in the next state”;
- F “There is some state in the future (eventually)”;
- G “Globally (in all future states)”;
- $\varphi U \psi$: φ is true at least until ψ becomes true;

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- Notice that, in CTL, the combination of path specific operators and temporal operators are atomic, e.g., AF is an atomic operator that can be read as “In all paths in the future there is some state where...”;

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- Notice as well that the binary operators $A[\varphi U \psi]$ and $E[\varphi U \psi]$ can be represented as AU and EU , respectively;

- Notice that, in CTL, the combination of path specific operators and temporal operators are atomic, e.g., AF is an atomic operator that can be read as “In all paths in the future there is some state where...”;
- Notice as well that the binary operators $A[\varphi U \psi]$ and $E[\varphi U \psi]$ can be represented as AU and EU , respectively;
- We assume that, similarly to the \neg operator, the “new” unary operators (AX , EX , AF , EF , AG , and EG) have the first precedence. Next comes the \wedge and \vee operators. And at last the \rightarrow , AU and EU ;

Examples

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL

Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

■ Examples of well-formed formulas:

- $AG(p \vee EFq)$

Examples

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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Examples

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

■ Examples of well-formed formulas:

- $AG(p \vee EFq)$
- $AX(q \rightarrow E[(p \vee q)Ur])$
- $EFEGp \rightarrow AFr$ Note that this is binded as
 $(EFEGp) \rightarrow AFr$, not as $EFEG(p \rightarrow AFr)$

Examples

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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- Example of formulas that are not well-formed:
 - $A\neg G\neg p$

Examples

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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Examples

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate

Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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- Example of formulas that are not well-formed:
 - $A\neg G\neg p$
 - $F[pUs]$
 - $A[pUs \wedge qUs]$

Semantics

Definition of model

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Definition

Let *Atoms* be a set of atomic formulas. A **transition system** or **model** $\mathcal{M} = (S, \rightarrow, L)$ in which S is a set of states, \rightarrow is a binary relation over S ($\rightarrow \subseteq S \times S$) such that for every state $s \in S$, exists a s' that $s \rightarrow s'$ and $L : S \rightarrow \mathcal{P}(\text{Atoms})$ (or $L : S \rightarrow (\text{Atoms} \rightarrow \{0, 1\})$) is a labelling function.

Semantics

Definition of model

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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Let *Atoms* be a set of atomic formulas. A **transition system** or **model** \mathcal{M} is a triple $\mathcal{M} = (S, \rightarrow, L)$ in which S is a set of states, \rightarrow is a binary relation over S ($\rightarrow \subseteq S \times S$) such that for every state $s \in S$, exists a s' that $s \rightarrow s'$ and $L : S \rightarrow \mathcal{P}(\text{Atoms})$ (or $L : S \rightarrow (\text{Atoms} \rightarrow \{0, 1\})$) is a labelling function.

CTL formulas are satisfied by a transition system and a specific state.

Notation: we will use $\mathcal{M}, s \models \varphi$ to denote that the model \mathcal{M}, s satisfies the formula φ

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
**Semantics of
CTL**

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Definition

The **satisfaction** of a formula in CTL is recursive over the structure of the formula. It can be done as follows:

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

- $\mathcal{M}, s \models \top$ and $\mathcal{M}, s \not\models \perp$ for all $s \in S$

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

- $\mathcal{M}, s \models \top$ and $\mathcal{M}, s \not\models \perp$ for all $s \in S$
- $\mathcal{M}, s \models p$ iff $p \in L(s)$

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

- $\mathcal{M}, s \models \top$ and $\mathcal{M}, s \not\models \perp$ for all $s \in S$
- $\mathcal{M}, s \models p$ iff $p \in L(s)$
- $\mathcal{M}, s \models \neg\varphi$ iff $\mathcal{M}, s \not\models \varphi$

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

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- $\mathcal{M}, s \models p$ iff $p \in L(s)$
- $\mathcal{M}, s \models \neg\varphi$ iff $\mathcal{M}, s \not\models \varphi$
- $\mathcal{M}, s \models \varphi_1 \wedge \varphi_2$ iff $\mathcal{M}, s \models \varphi_1$ AND $\mathcal{M}, s \models \varphi_2$

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

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- $\mathcal{M}, s \models \varphi_1 \wedge \varphi_2$ iff $\mathcal{M}, s \models \varphi_1$ AND $\mathcal{M}, s \models \varphi_2$
- $\mathcal{M}, s \models \varphi_1 \vee \varphi_2$ iff $\mathcal{M}, s \models \varphi_1$ OR $\mathcal{M}, s \models \varphi_2$

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Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

- $\mathcal{M}, s \models AX\varphi$ iff for all s_1 that $s \rightarrow s_1$ and $\mathcal{M}, s_1 \models \varphi$.
Thus, AX says: “in every next state...”

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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Thus, AX says: “in every next state...”
- $\mathcal{M}, s \models EX\varphi$ iff exists s_1 that $s \rightarrow s_1$ and $\mathcal{M}, s_1 \models \varphi$. Thus,
 EX says: “in some next state...”

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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Thus, AX says: “in every next state...”
- $\mathcal{M}, s \models EX\varphi$ iff exists s_1 that $s \rightarrow s_1$ and $\mathcal{M}, s_1 \models \varphi$. Thus,
 EX says: “in some next state...”
- $\mathcal{M}, s \models AG\varphi$ iff for all paths $s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \dots$ in which $s = s_1$, for all s_i , $\mathcal{M}, s_i \models \varphi$. Thus, AG says: “In all possible paths from now on in all next states...”

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

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possible paths from now on in all next states...”
- $\mathcal{M}, s \models EG\varphi$ iff exists some path $s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \dots$ in
which $s = s_1$, for all s_i , $\mathcal{M}, s_i \models \varphi$. Thus, EG says: “Exists
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Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silva

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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- $\mathcal{M}, s, \models AF\varphi$ iff for all paths $s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \dots$ in which $s = s_1$, exists $s_i, \mathcal{M}, s_i \models \varphi$. Thus, AF says: “In all possible paths from now on, in some next state...”

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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- $\mathcal{M}, s, \models EF\varphi$ iff exists some path $s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \dots$ in which $s = s_1$, that exists $s_i, \mathcal{M}, s_i \models \varphi$. Thus, EF says: “In some path from now on, in some next state...”

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

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- $\mathcal{M}, s, \models EF\varphi$ iff exists some path $s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \dots$ in which $s = s_1$, that exists s_i , $\mathcal{M}, s_i \models \varphi$. Thus, EF says: “In some path from now on, in some next state...”
- $\mathcal{M}, s, \models A[\varphi_1 U \varphi_2]$ iff for all paths $s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \dots$ in which $s = s_1$, this path satisfies $\varphi_1 U \varphi_2$, i.e., exists s_j in the path such that $\mathcal{M}, s_j \models \varphi_2$ and, for all $j < i$, $\mathcal{M}, s_j \models \varphi_1$. Thus, AU says: “For all paths from now on, until some state...”

Semantics

Satisfaction

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Take an arbitrary model \mathcal{M} . Let s, s_1, s_2, s_3 be states in S . Let $\varphi, \varphi_1, \varphi_2$ be well-formed formulas of CTL. And let p be an atom. The satisfaction of CTL formulas can be defined as follows:

- $\mathcal{M}, s, \models E[\varphi_1 U \varphi_2]$ iff exists some path $s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow \dots$ in which $s = s_1$, this path satisfies $\varphi_1 U \varphi_2$. Thus, EU says: “In some path from now on, until some state...”

Examples

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- “It’s possible to get to a state where something has started but it’s not ready”: $EF(started \wedge \neg ready)$

Examples

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- “It’s possible to get to a state where something has started but it’s not ready”: $EF(started \wedge \neg ready)$
- “A certain process is enabled infinitely often on every computation path”: $AG(AF enabled)$

Examples

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- “It’s possible to get to a state where something has started but it’s not ready”: $EF(started \wedge \neg ready)$
- “A certain process is enabled infinitely often on every computation path”: $AG(AGF enabled)$
- “An upwards travelling lift at the second floor does not change its direction when it has passengers wishing to go to the fifth floor”:
 $AG(floor2 \wedge directionup \wedge button5 \rightarrow A[directionup U floor5])$

Equivalences

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Definition

Two CTL formulas φ and ψ are said to be **semantically equivalent** if any state in any model which satisfies one of them also satisfies the other;

Equivalences

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Definition

Two CTL formulas φ and ψ are said to be **semantically equivalent** if any state in any model which satisfies one of them also satisfies the other;

Notation: we denote the semantic equivalence of φ and ψ by
$$\varphi \equiv \psi$$

Example of equivalences

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics

Equivalences

Improving our
language

Let φ be an arbitrary CTL formula.

$$\blacksquare \neg AF\varphi \equiv EG\neg\varphi$$

Example of equivalences

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics

Equivalences

Improving our
language

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Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Let φ be an arbitrary CTL formula.

$$\blacksquare \neg AF\varphi \equiv EG\neg\varphi$$

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$$\blacksquare \neg AX\varphi \equiv EX\neg\varphi$$

Example of equivalences

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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$$\blacksquare AF\varphi \equiv A[\top U \varphi]$$

Example of equivalences

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

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$$\blacksquare AF\varphi \equiv A[\top U\varphi]$$

$$\blacksquare EF\varphi \equiv E[\top U\varphi]$$

Minimum set of CTL connectives

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Because of the equivalences shown and the ones in propositional logic, we can have some minimum sets of connectives for the CTL syntax. One of them is defined in Backus-Naur formalism below:

$$\phi ::= \perp \mid p \mid \neg\phi \mid \phi \wedge \phi \mid EX\phi \mid AF\phi \mid E[\phi U \phi]$$

That's all we need?

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Even if CTL allow explicit quantification over paths, it cannot allow some expressions to be formed. For example, we cannot say, as in LTL: "All paths in which have p on them, also have q on them".

This expression can be translated in LTL as follows:

$$Fp \rightarrow Fq$$

That's all we need?

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

We can try expressing it as $AFp \rightarrow AFq$ but it does not have the same meaning. This one statement means "If all paths have a p along them, then all paths have a q along then"

That's all we need?

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

We can try expressing it as $AFp \rightarrow AFq$ but it does not have the same meaning. This one statement means "If all paths have a p along them, then all paths have a q along then"

We can try to translate it as $AG(p \rightarrow AFq)$ which is closer, but not exactly the same. This one means "for all paths, in all states on the future, if they hold p then, all paths will eventually hold q "

Presenting CTL*

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

For this, we can extend the CTL by dropping the constraint that every temporal operator (X , U , F , G) has to be associated with an unique path quantifier (A , E).

Presenting CTL*

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

For this, we can extend the CTL by dropping the constraint that every temporal operator (X , U , F , G) has to be associated with an unique path quantifier (A , E).

This allows us to generate some statements:

Presenting CTL*

Statements only possible with CTL*

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- “In all possible paths, q is true until r is true or p is true until r is true”: $A[qUr \vee pUr]$

Presenting CTL*

Statements only possible with CTL*

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- “In all possible paths, q is true until r is true or p is true until r is true”: $A[qUr \vee pUr]$
- “There is a path in which p eventually occurring will occur in all states”: $E[GFp]$

Presenting CTL*

Statements only possible with CTL*

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

- “In all possible paths, q is true until r is true or p is true until r is true”: $A[qUr \vee pUr]$
- “There is a path in which p eventually occurring will occur in all states”: $E[GFp]$
- “In all paths, p will occur in the next state or in the next of the next”: $A[Xp \vee XXp]$

Presenting CTL*

CTL* syntax

Computation
Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

The syntax of CTL* can be defined with the BNF bellow:

$$\phi ::= \perp \mid \top \mid p \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \phi \rightarrow \phi \mid A[\alpha] \mid E[\alpha] \mid$$

$$\alpha ::= \phi \mid \neg\alpha \mid \alpha \wedge \alpha \mid \alpha \vee \alpha \mid \alpha \rightarrow \alpha \mid \alpha U \alpha \mid G\alpha \mid F\alpha \mid X\alpha \mid$$

With the same meanings of each operator.

Presenting CTL*

$LTL \subset CTL^*$ and $CTL \subset CTL^*$

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Although we don't define path operators to LTL we can assume that it consider in all paths. Therefore, we can say that a formula ϕ in LTL is a formula $A[\phi]$ in CTL^* ;

Presenting CTL*

$LTL \subset CTL^*$ and $CTL \subset CTL^*$

Computation Tree Logic

Luis Tertulino &
Ronaldo Silveira

In previous
chapters...

Introduction

How to
communicate
Syntax of CTL
Semantics of
CTL

Some examples of
what we can say

More about
semantics
Equivalences

Improving our
language

Although we don't define path operators to LTL we can assume that it consider in all paths. Therefore, we can say that a formula ϕ in LTL is a formula $A[\phi]$ in CTL^* ;
For CTL, it is trivial;