Overview

Introduction

Modelling parallel systems

Linear Time Properties

Regular Properties

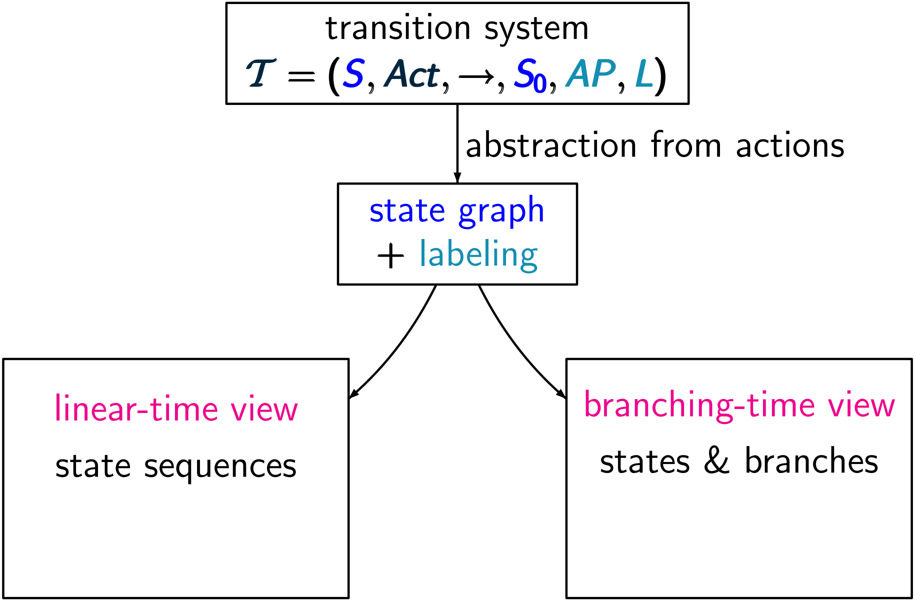
Linear Temporal Logic (LTL)

Computation Tree Logic

Equivalences and Abstraction

Linear vs branching time

Linear vs branching time



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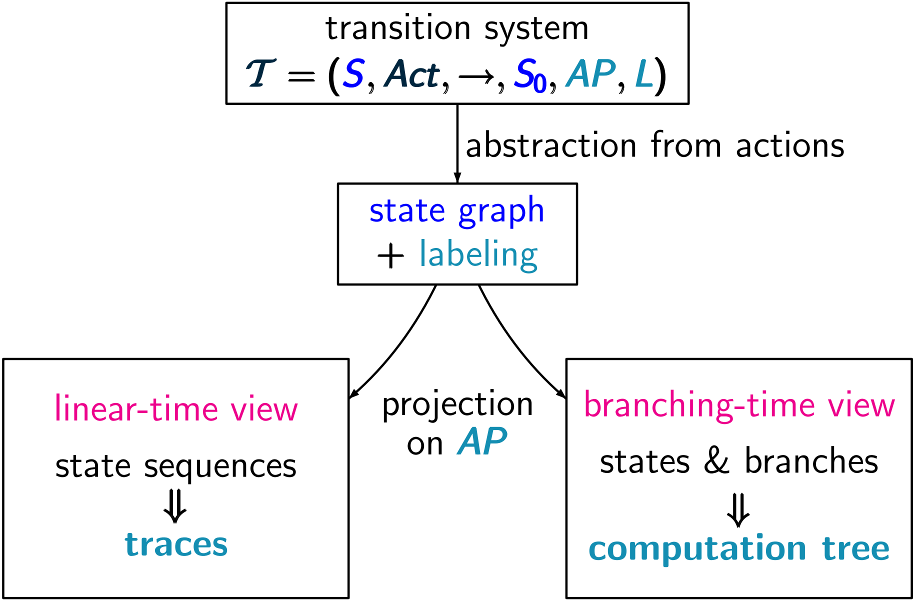

Computation tree

Computation tree

The computation tree of a transition system $\mathcal{T} = (S, Act, \rightarrow, s_0, AP, L)$ arises by:

- unfolding into a tree
- abstraction from the actions
- projection of the states s to their labels $L(s) \subseteq AP$

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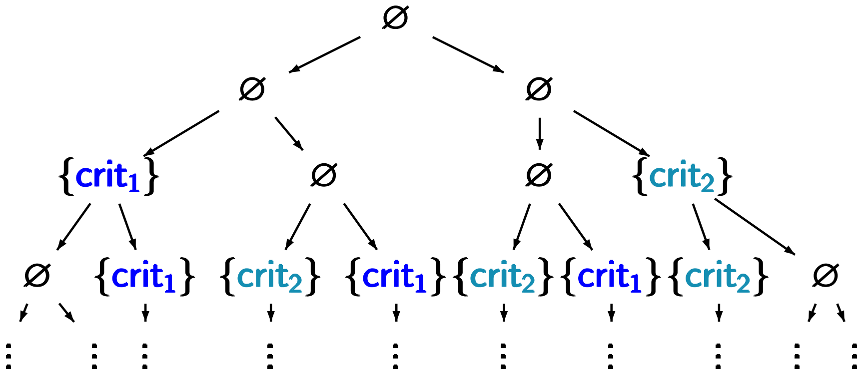
Example: computation tree

mutual exclusion with semaphore and $AP = \{crit_1, crit_2\}$:



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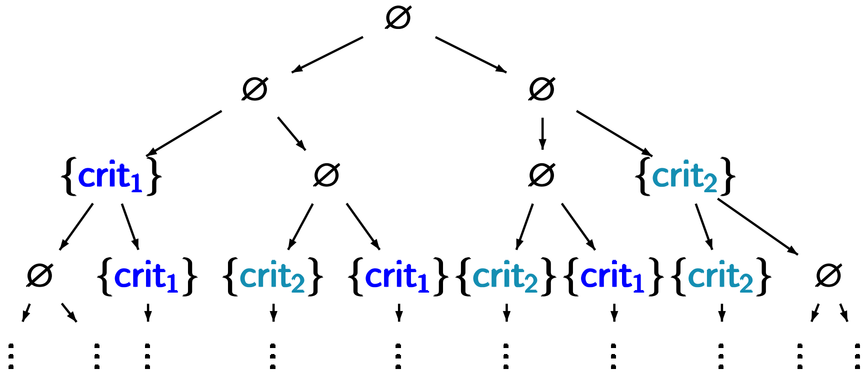

path $\langle nc_1, nc_2 \rangle$ $\langle wait_1, nc_2 \rangle$ $\langle crit_1, nc_2 \rangle$ $\langle crit_1, wait_2 \rangle$ ...

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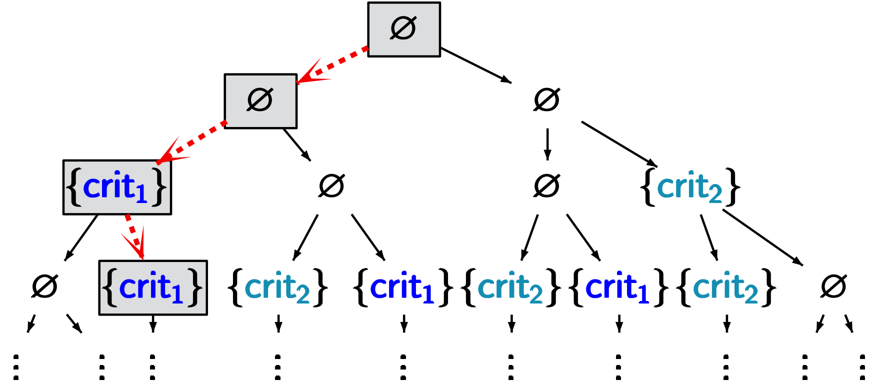

path	$\langle nc_1, nc_2 \rangle$	$\langle wait_1, nc_2 \rangle$	$\langle crit_1, nc_2 \rangle$	$\langle crit_1, wait_2 \rangle$	...
↓	↓	↓	↓	↓	
trace	$\varnothing$	$\varnothing$	$\{crit_1\}$	$\{crit_1\}$	...

Linear vs. branching time

	linear time	branching time
behavior	path based	state based

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fairness	can be encoded	requires special treatment

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Computation Tree Logic

- syntax and semantics of CTL ⟵
- expressiveness of CTL and LTL
- CTL model checking
- fairness, counterexamples/witnesses
- CTL^+ and CTL^*

Equivalences and Abstraction

Computation Tree Logic (CTL)

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CTL (state) formulas:

$$\Phi ::= \textit{true} \mid a \mid \Phi_1 \wedge \Phi_2 \mid \neg\Phi \mid \exists\varphi \mid \forall\varphi$$

CTL path formulas:

$$\varphi ::= \bigcirc\Phi \mid \Phi_1 \, \mathsf{U} \, \Phi_2$$

CTL (state) formulas:

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$$\exists\Diamond\Phi \quad \stackrel{\text{def}}{=} \quad \exists(\mathit{true}\,\mathsf{U}\,\Phi)$$

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reset possiblity $\forall\Box\exists\Diamond start$

unconditional process fairness $\forall\Box\forall\Diamond crit_1 \wedge \forall\Box\forall\Diamond crit_2$

Example: 15-puzzle

6	8	2	12
4	1	13	5
	9	10	14
7	11	15	3

$\overset{?}{\rightsquigarrow}$

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$\uparrow$

states:	game configurations
transitions:	legal moves

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  with shared variables $\mathit{field}[i]$ for $i = 1, \ldots, 16$

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CTL specification: seeking for a **witness** for

$$\exists\Diamond \bigwedge_{1 \leq i \leq 15} \text{"}\textit{piece } i \text{ on } \textit{field}[i]\text{"}$$

Semantics of CTL

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define a satisfaction relation $\models$ for CTL formulas over AP and a given TS $\mathcal{T} = (S, Act, \rightarrow, S_0, AP, L)$

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- interpretation of state formulas over the states
- interpretation of path formulas over the paths (infinite path fragments)

Recall: semantics of LTL

for infinite path fragment $\pi = s_0\, s_1\, s_2\, \ldots$:

$\pi \models \mathit{true}$		
$\pi \models a$	iff	$s_0 \models a$,i.e., $a \in L(s_0)$
$\pi \models \varphi_1 \wedge \varphi_2$	iff	$\pi \models \varphi_1$ and $\pi \models \varphi_2$
$\pi \models \neg\varphi$	iff	$\pi \not\models \varphi$
$\pi \models \bigcirc\varphi$	iff	$\mathit{suffix}(\pi, 1) = s_1\, s_2\, s_3\, \ldots \models \varphi$
$\pi \models \varphi_1 \mathsf{U}\, \varphi_2$	iff	there exists $j \geq 0$ such that

$\mathit{suffix}(\pi, j) = s_j\ s_{j+1}\ s_{j+2}\ \ldots \models \varphi_2$ and

$\mathit{suffix}(\pi, k) = s_k\, s_{k+1}\, s_{k+2}\, \ldots \models \varphi_1$ for $0 \leq k < j$

Satisfaction relation for path formulas

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semantics of derived operators:

$\pi \models \Diamond \Phi$ iff there exists $j \geq 0$ with $s_j \models \Phi$

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semantics of derived operators:

$$\pi \models \Diamond \Phi \quad \text{iff} \quad \text{there exists } j \geq 0 \text{ with } \quad s_j \models \Phi$$

$$\pi \models \Box \Phi \quad \text{iff} \quad \text{for all } j \geq 0 \text{ we have: } \quad s_j \models \Phi$$

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satisfaction set for state formula Φ:

$$Sat(\Phi) \stackrel{\text{def}}{=} \{s \in S : s \models \Phi\}$$

Interpretation of CTL formulas over a TS

Interpretation of CTL formulas over a TS

satisfaction of state formulas over a TS $\mathcal{T}$:

$$\mathcal{T} \models \Phi \quad \text{iff} \quad S_0 \subseteq Sat(\Phi)$$

where S_0 is the set of initial states

recall: $Sat(\Phi) = \{ s \in S : s \models \Phi \}$

satisfaction of state formulas over a TS $\mathcal{T}$:

$$\mathcal{T} \models \Phi \quad \text{iff} \quad S_0 \subseteq Sat(\Phi)$$
$$\text{iff} \quad s_0 \models \Phi \text{ for all initial states } s_0 \text{ of } \mathcal{T}$$

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Semantics of the next operator

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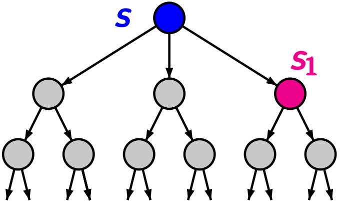

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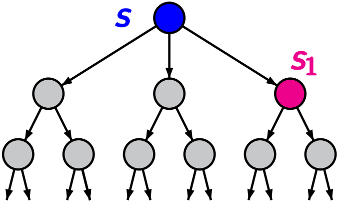
$s \models \forall\bigcirc\Phi$ iff for all $\pi = s\, s_1\, s_2\, \ldots \in Paths(s)$: $\pi \models \bigcirc\Phi$

$\exists\bigcirc\Phi$



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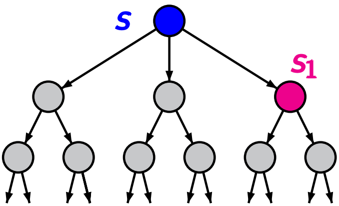
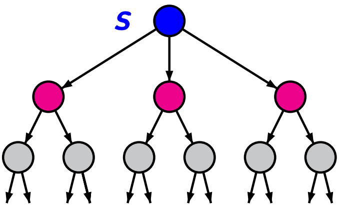
$s \models \forall \bigcirc \Phi$ iff for all $\pi = s\, s_1\, s_2 \ldots \in Paths(s)$: $\pi \models \bigcirc \Phi$, i.e., $s_1 \models \Phi$

$\exists \bigcirc \Phi$



$Post(s) \cap Sat(\Phi) \neq \varnothing$

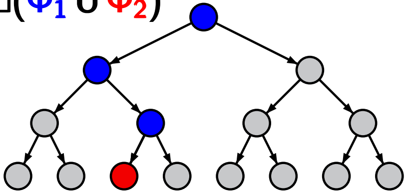
$\forall \bigcirc \Phi$



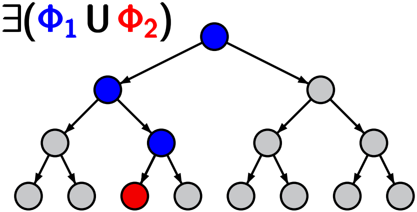
$Post(s) \subseteq Sat(\Phi)$

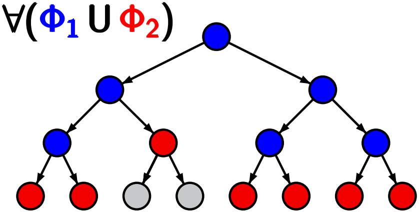
Semantics of until

$\exists(\Phi_1 \, \mathsf{U} \, \Phi_2)$



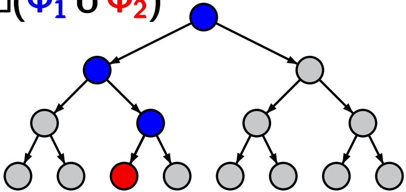
Semantics of until



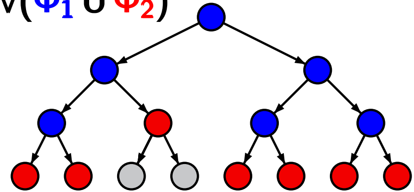


Semantics of until and eventually

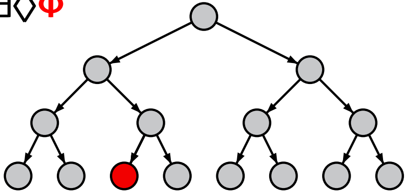
$\exists(\Phi_1 \, \mathsf{U} \, \Phi_2)$



$\forall(\Phi_1 \, \mathsf{U} \, \Phi_2)$

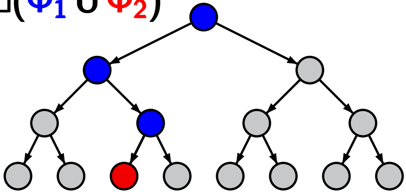


$\exists\Diamond\Phi$

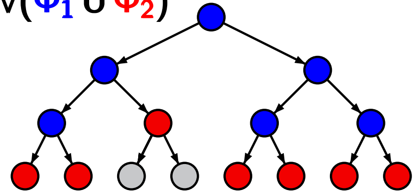


Semantics of until and eventually

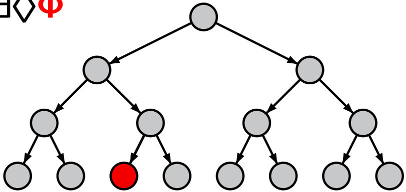
$\exists(\Phi_1 \, \mathsf{U} \, \Phi_2)$



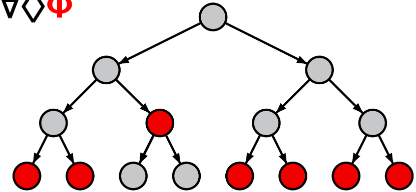
$\forall(\Phi_1 \, \mathsf{U} \, \Phi_2)$



$\exists\Diamond\Phi$

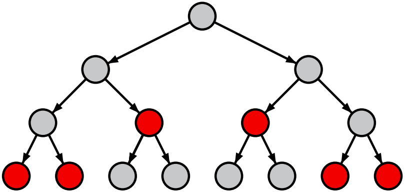


$\forall\Diamond\Phi$

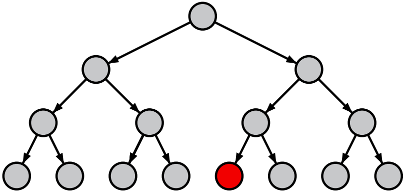


Semantics of eventually and always

$\forall\Diamond\Phi$

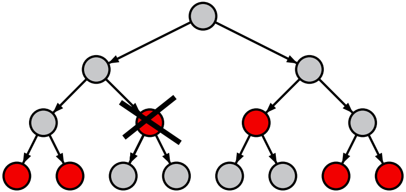


$\exists\Diamond\Phi$

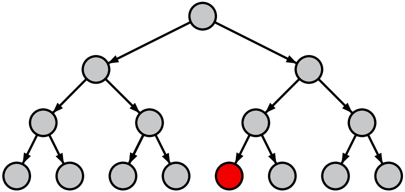


Semantics of eventually and always

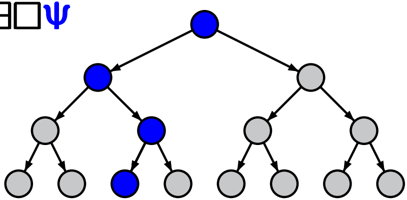
$\neg\forall\Diamond\Phi$



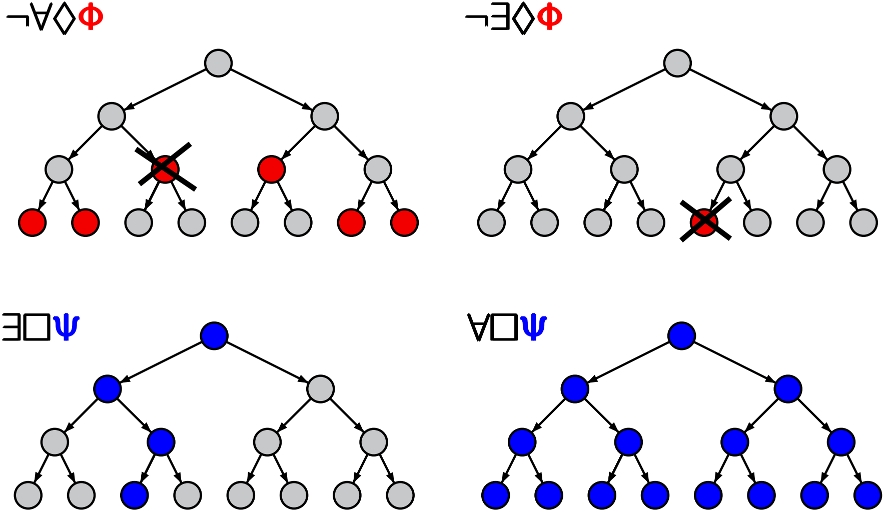
$\exists\Diamond\Phi$



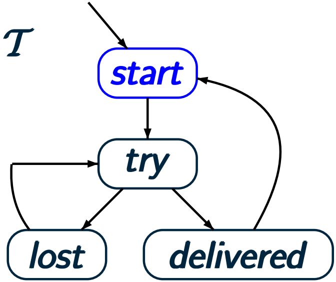
$\exists\Box\Psi$



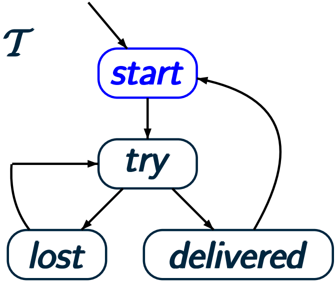
Semantics of eventually and always



Example for CTL semantics



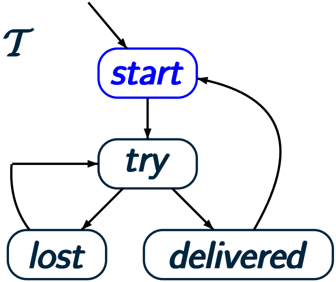
Example for CTL semantics



CTL formula

$\Phi = \forall\Box\forall\Diamond \textit{start}$

Example for CTL semantics

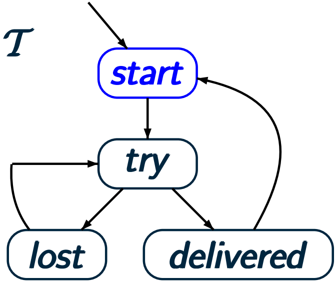


CTL formula

$\Phi = \forall\Box\ \boxed{\forall\Diamond start}$

$Sat(\forall\Diamond start) = \ ?$

Example for CTL semantics

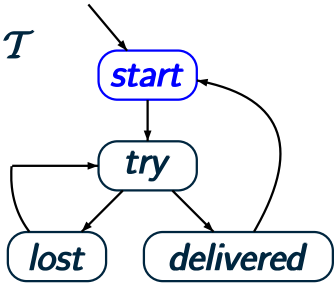


CTL formula

$\Phi = \forall\Box\ \boxed{\forall\Diamond start}$

$Sat(\forall\Diamond start) = \{start, delivered\}$

Example for CTL semantics

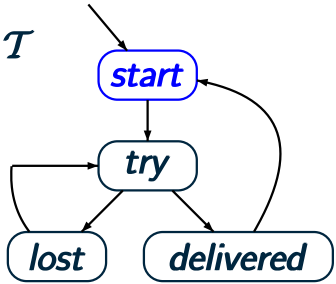


CTL formula

$\Phi = \forall\Box\forall\Diamond start \quad \hat{=} \quad \forall\Box(start \vee delivered)$

$Sat(\forall\Diamond start) = \{start, delivered\}$

Example for CTL semantics



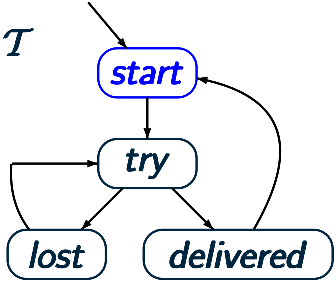
CTL formula

$$\Phi = \forall\Box\forall\Diamond start \;\hat{=}\; \forall\Box(start \vee delivered)$$

$$Sat(\forall\Diamond start) = \{start, delivered\}$$

$$Sat(\Phi) = \varnothing$$

Example for CTL semantics



$\mathcal{T} \not\models \forall\Box\forall\Diamond start$

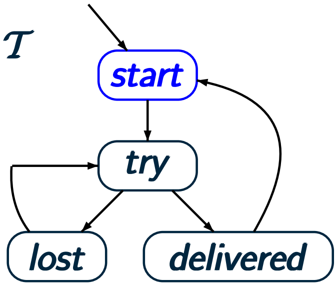
CTL formula

$\Phi = \forall\Box\forall\Diamond start \quad \widehat{=} \quad \forall\Box(start \vee delivered)$

$$Sat(\forall\Diamond start) = \{start, delivered\}$$

$$Sat(\Phi) = \varnothing$$

Example for CTL semantics



$\mathcal{T} \not\models \forall\Box\forall\Diamond \mathit{start}$

"infinitely often *start*"

CTL formula

$\Phi = \forall\Box\forall\Diamond \mathit{start} \quad \widehat{=} \quad \forall\Box(\mathit{start} \vee \mathit{delivered})$

$$\mathit{Sat}(\forall\Diamond \mathit{start}) = \{\mathit{start}, \mathit{delivered}\}$$

$$\mathit{Sat}(\Phi) = \varnothing$$

Specifying "infinitely often" in CTL

If s is a state in a TS and $a \in AP$ then:

$$s \models_{\text{CTL}} \forall\Box\forall\Diamond a$$

iff for all paths $\pi = s_0\, s_1\, s_2 \ldots \in Paths(s)$:

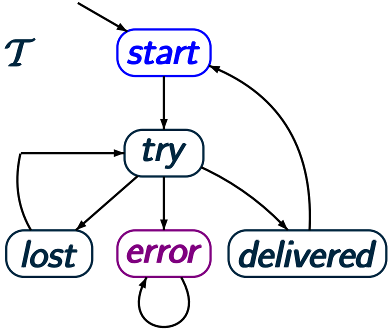
$$\overset{\infty}{\exists}\, i \geq 0. \quad \text{s.t.} \quad s_i \models a$$

Specifying "infinitely often" in CTL

If s is a state in a TS and $a \in AP$ then:

	$s \models_{\text{CTL}} \forall\Box\forall\Diamond a$
iff	for all paths $\pi = s_0\, s_1\, s_2 \ldots \in Paths(s)$:
	$\overset{\infty}{\exists}\, i \geq 0.$ s.t. $s_i \models a$
iff	$s \models_{\text{LTL}} \Box\Diamond a$

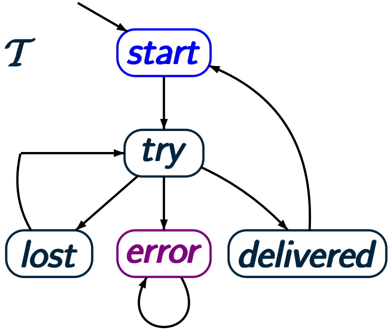
Example: CTL semantics



$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$ **?**

$\Phi_1 = \exists\Diamond\forall\Box\neg start$

Example: CTL semantics

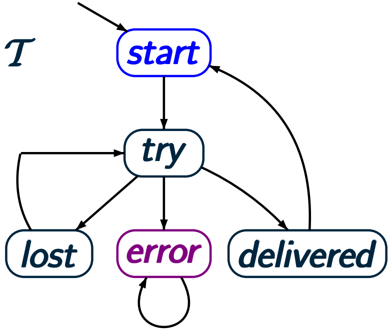


$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$ **?**

$\Phi_1 = \exists\Diamond \boxed{\forall\Box\neg start}$

$Sat(\forall\Box\neg start) = \{error\}$

Example: CTL semantics



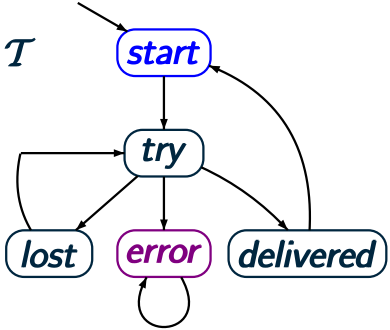
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$?

$$\Phi_1 = \exists\Diamond \boxed{\forall\Box\neg start} \rightsquigarrow \exists\Diamond \boxed{error}$$

$$Sat(\forall\Box\neg start) = \{error\}$$

$$Sat(\exists\Diamond\forall\Box\neg start) = \text{?}$$

Example: CTL semantics



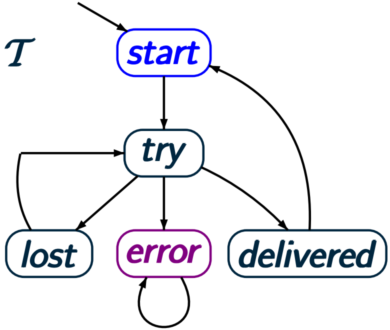
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$ ✓

$\Phi_1 = \exists\Diamond \boxed{\forall\Box\neg start} \rightsquigarrow \exists\Diamond \boxed{error}$

$Sat(\forall\Box\neg start) = \{error\}$

$Sat(\exists\Diamond\forall\Box\neg start) = Sat(\exists\Diamond error) =$ "all states"

Example: CTL semantics

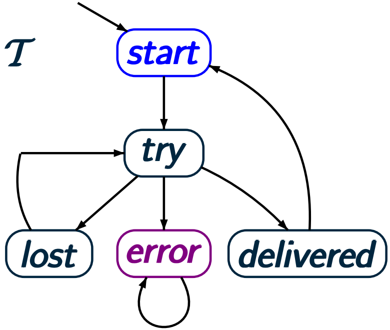


$\Phi_2 = \forall \bigcirc \exists \bigcirc \forall \Box \neg start$

$\mathcal{T} \models \exists \Diamond \forall \Box \neg start$

$\mathcal{T} \models \forall \bigcirc \exists \bigcirc \forall \Box \neg start$ **?**

Example: CTL semantics

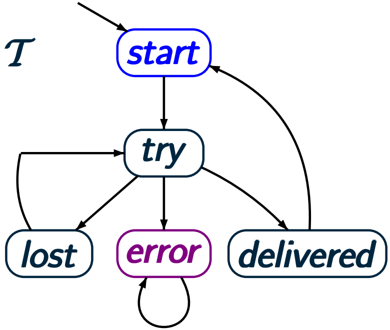


$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$ **?**

$\Phi_2 = \forall\bigcirc\exists\bigcirc \boxed{\forall\Box\neg start}$

$$Sat(\forall\Box\neg start) = \{error\}$$



$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$?

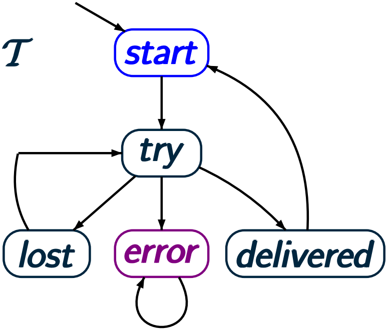
$\Phi_2 = \forall\bigcirc \; \boxed{\exists\bigcirc\forall\Box\neg start} \quad \rightsquigarrow \quad \forall\bigcirc \; \boxed{\exists\bigcirc error}$

$$Sat(\forall\Box\neg start) = \{error\}$$

$$Sat(\exists\bigcirc\forall\Box\neg start) = \{error, try\}$$

Example: CTL semantics

$\mathcal{T}$



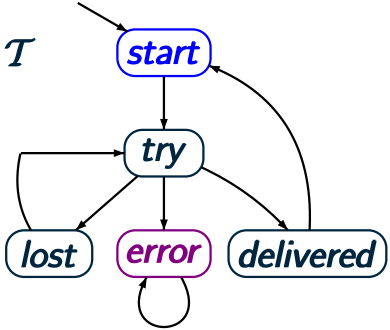
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$?

$\Phi_2 = \forall\bigcirc\exists\bigcirc\forall\Box\neg start \quad \rightsquigarrow \quad \forall\bigcirc(error \vee try)$

$$Sat(\forall\Box\neg start) = \{error\}$$
$$Sat(\exists\bigcirc\forall\Box\neg start) = \{error, try\}$$
$$Sat(\forall\bigcirc\exists\bigcirc\forall\Box\neg start) = ?$$

Example: CTL semantics



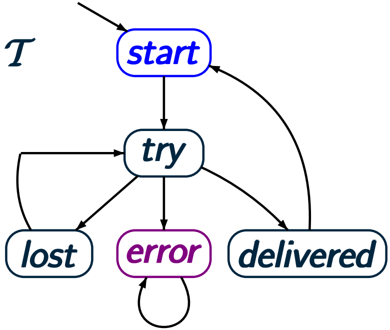
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$ $\surd$

$\Phi_2 = \forall\bigcirc\exists\bigcirc\forall\Box\neg start \rightsquigarrow \forall\bigcirc(error \vee try)$

$$Sat(\forall\Box\neg start) = \{error\}$$
$$Sat(\exists\bigcirc\forall\Box\neg start) = \{error, try\}$$
$$Sat(\forall\bigcirc\exists\bigcirc\forall\Box\neg start) = \{error, lost, start\}$$

Example: CTL semantics



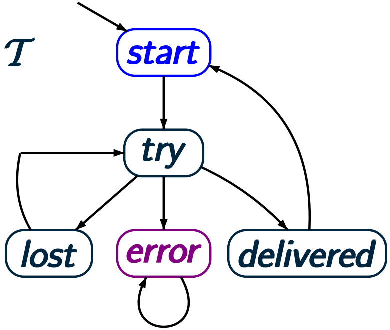
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

$\mathcal{T} \models \exists\bigcirc\forall\bigcirc\forall\Box\neg start$ **?**

$\Phi_3 = \exists\bigcirc\forall\bigcirc\forall\Box\neg start$

Example: CTL semantics



$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

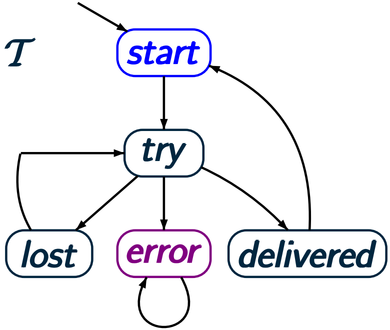
$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

$\mathcal{T} \models \exists\bigcirc\forall\bigcirc\forall\Box\neg start$ **?**

$\Phi_3 = \exists\bigcirc\forall\bigcirc \boxed{\forall\Box\neg start}$

$Sat(\forall\Box\neg start) = \{error\}$

Example: CTL semantics



$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

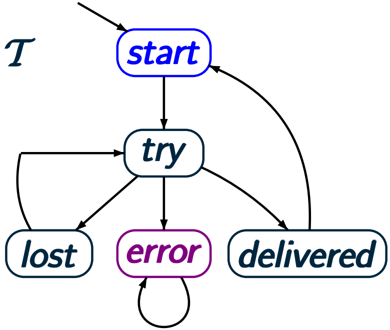
$\mathcal{T} \models \exists\bigcirc\forall\bigcirc\forall\Box\neg start$ **?**

$\Phi_3 = \exists\bigcirc \boxed{\forall\bigcirc\forall\Box\neg start} \rightsquigarrow \exists\bigcirc \boxed{\forall\bigcirc error}$

$$Sat(\forall\Box\neg start) = \{error\}$$

$$Sat(\forall\bigcirc\forall\Box\neg start) = \{error\}$$

Example: CTL semantics



$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

$\mathcal{T} \models \exists\bigcirc\forall\bigcirc\forall\Box\neg start$?

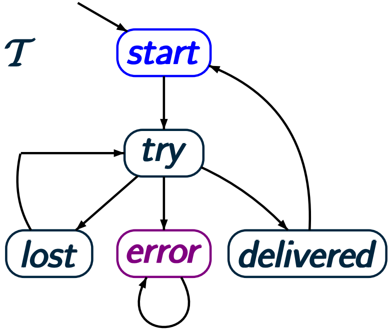
$\Phi_3 = \exists\bigcirc\forall\bigcirc\forall\Box\neg start \rightsquigarrow \boxed{\exists\bigcirc error}$

$$Sat(\forall\Box\neg start) = \{error\}$$

$$Sat(\forall\bigcirc\forall\Box\neg start) = \{error\}$$

$$Sat(\exists\bigcirc\forall\bigcirc\forall\Box\neg start) = \ ?$$

Example: CTL semantics



$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

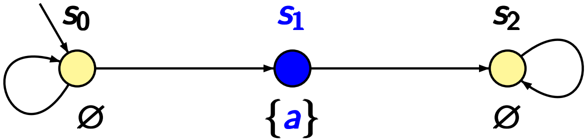
$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

$\mathcal{T} \not\models \exists\bigcirc\forall\bigcirc\forall\Box\neg start$

$\Phi_3 = \exists\bigcirc\forall\bigcirc\forall\Box\neg start \rightsquigarrow \boxed{\exists\bigcirc error}$

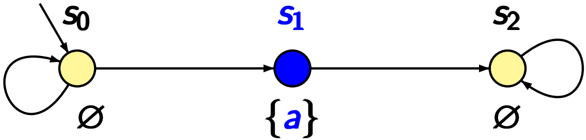
$$Sat(\forall\Box\neg start) = \{error\}$$
$$Sat(\forall\bigcirc\forall\Box\neg start) = \{error\}$$
$$Sat(\exists\bigcirc\forall\bigcirc\forall\Box\neg start) = \{error, try\}$$

Example: CTL semantics



does $\mathcal{T} \models \exists \bigcirc \forall \Box \neg a$ hold ?

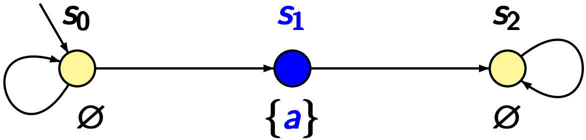
Example: CTL semantics



does $\mathcal{T} \models \exists \bigcirc \forall \Box \neg a$ hold ?

answer: no

Example: CTL semantics

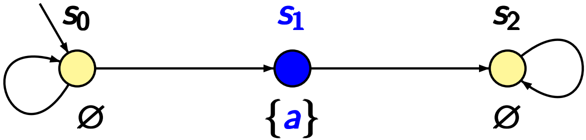


does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

answer: no

$$Sat(\forall\Box\neg a) \;=\; \{s_2\}$$

Example: CTL semantics

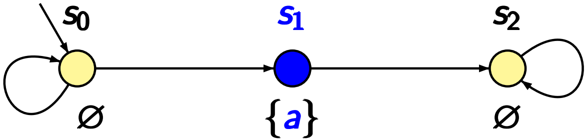


does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

answer: no

$$Sat(\forall\Box\neg a) = \{s_2\}$$
$$Sat(\exists\bigcirc\forall\Box\neg a) = \{s_2, s_1\}$$

Example: CTL semantics

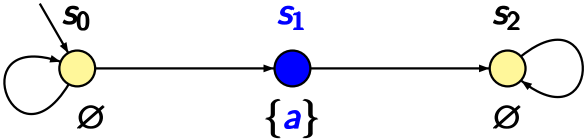


does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

answer: no

does $\mathcal{T} \models \forall\Box\exists\bigcirc\neg a$ hold ?

Example: CTL semantics



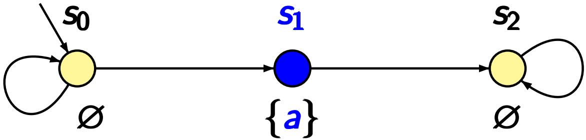
does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

answer: no

does $\mathcal{T} \models \forall\Box\exists\bigcirc\neg a$ hold ?

answer: yes

Example: CTL semantics



does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

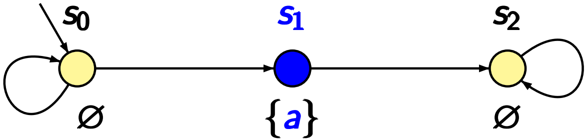
answer: no

does $\mathcal{T} \models \forall\Box\exists\bigcirc\neg a$ hold ?

answer: yes

$$Sat(\exists\bigcirc\neg a) = \{s_0, s_1, s_2\}$$

Example: CTL semantics



does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

answer: no

does $\mathcal{T} \models \forall\Box\exists\bigcirc\neg a$ hold ?

answer: yes

$$Sat(\exists\bigcirc\neg a) = \{s_0, s_1, s_2\}$$
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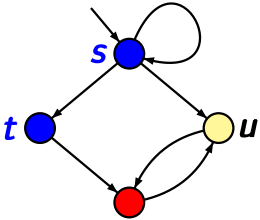

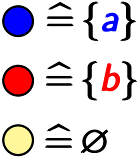

$\mathcal{T} \models \exists\Box\exists(a \,\mathsf{U}\, b)$?

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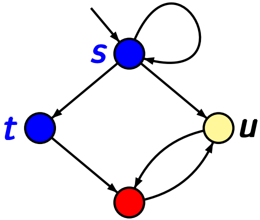

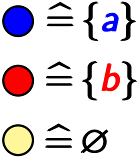

$\mathcal{T} \models \exists\Box\exists(a \,\mathsf{U}\, b)$ √ as $s \models \exists(a \,\mathsf{U}\, b)$

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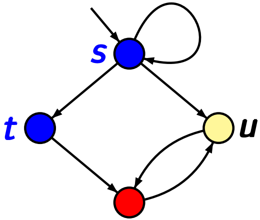
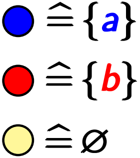
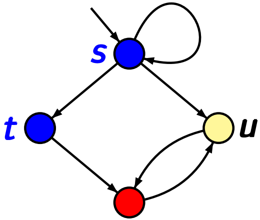
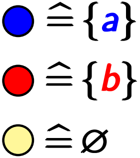




$\mathcal{T} \models \exists\Box\exists(a \,\mathsf{U}\, b)$ $\quad\checkmark\quad$ as $s\,s\,s\,\ldots \models \Box\exists(a \,\mathsf{U}\, b)$

Example: CTL semantics





$\mathcal{T} \models \exists\Box\exists(a \mathsf{U} b)$ ✓ as $s\,s\,s\,\ldots \models \Box\exists(a \mathsf{U} b)$

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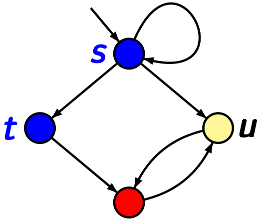

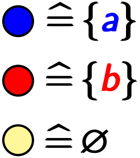

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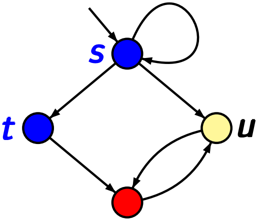

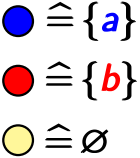

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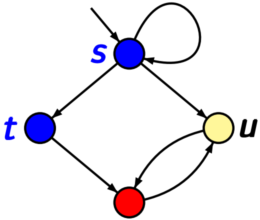

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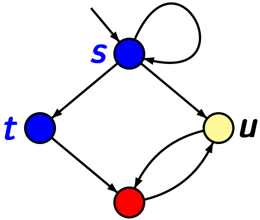

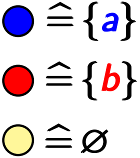

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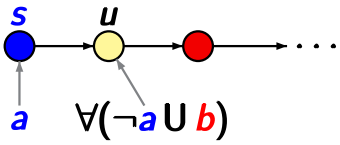

$\models a \mathsf{U} \forall(\neg a \mathsf{U} b)$

Correct or wrong?

Let $\mathcal{T}$ be a transition system and Φ a CTL formula.
Is the following statement correct **?**

$$\text{if} \quad \mathcal{T} \not\models \neg\Phi \quad \text{then} \quad \mathcal{T} \models \Phi$$

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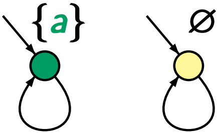
transition system $\mathcal{T}$ with 2 initial states:



$\mathcal{T} \not\models \exists\Box a$

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Hamilton path problem

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question: does G have a Hamilton path, i.e., a path that visits each node exactly once **?**

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CTL-encoding of the Hamilton path problem

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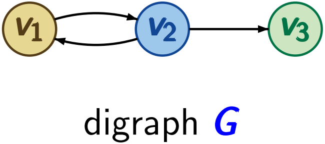
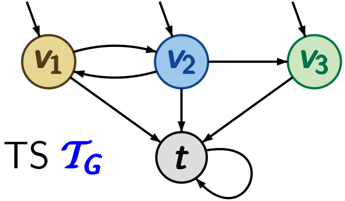


$\rightsquigarrow$



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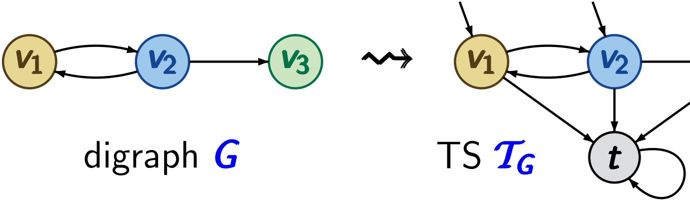

digraph G TS $\mathcal{T}_G$

CTL formula Φ

$$(v_1 \wedge \exists\bigcirc(v_2 \wedge \exists\bigcirc v_3)) \vee (v_1 \wedge \exists\bigcirc(v_3 \wedge \exists\bigcirc v_2)) \vee$$
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$$(v_3 \wedge \exists\bigcirc(v_1 \wedge \exists\bigcirc v_2)) \vee (v_3 \wedge \exists\bigcirc(v_2 \wedge \exists\bigcirc v_1))$$

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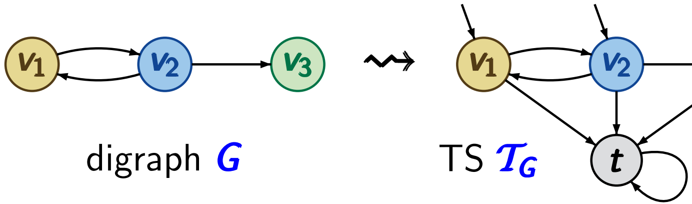

CTL formula Φ = negation of the formula

$$(v_1 \wedge \exists\bigcirc(v_2 \wedge \exists\bigcirc v_3)) \vee (v_1 \wedge \exists\bigcirc(v_3 \wedge \exists\bigcirc v_2)) \vee$$
$$(v_2 \wedge \exists\bigcirc(v_1 \wedge \exists\bigcirc v_3)) \vee (v_2 \wedge \exists\bigcirc(v_3 \wedge \exists\bigcirc v_1)) \vee$$
$$(v_3 \wedge \exists\bigcirc(v_1 \wedge \exists\bigcirc v_2)) \vee (v_3 \wedge \exists\bigcirc(v_2 \wedge \exists\bigcirc v_1))$$

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$\Phi_1 \equiv \Phi_2$ iff for all transition systems $\mathcal{T}$:

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quantification over all transition systems $\mathcal{T}$

- without terminal states
- over *AP* if Φ_1 and Φ_2 are CTL formulas over *AP*

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Examples:

$$\neg\neg\Phi \equiv \Phi$$

$$\neg(\Phi \wedge \Psi) \equiv \neg\Phi \vee \neg\Psi$$

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$$\vdots$$

$$\neg\forall\bigcirc\Phi \equiv \exists\bigcirc\neg\Phi$$

Correct or wrong?

$$\exists\Diamond(a \wedge b) \equiv \exists\Diamond a \wedge \exists\Diamond b$$

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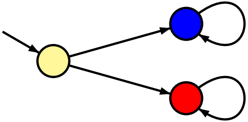
wrong, e.g,



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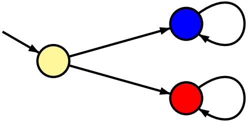

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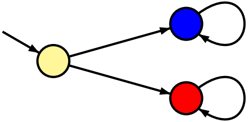

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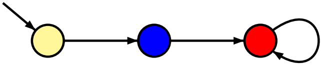

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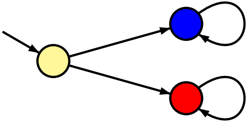

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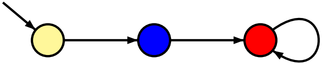

but:

$$\forall\Box(\Phi_1 \wedge \Phi_2) \equiv \forall\Box\Phi_1 \wedge \forall\Box\Phi_2$$
$$\exists\Diamond(\Phi_1 \vee \Phi_2) \equiv \exists\Diamond\Phi_1 \vee \exists\Diamond\Phi_2$$

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$$\forall\bigcirc\forall\Box a \equiv \forall\Box\forall\bigcirc a$$

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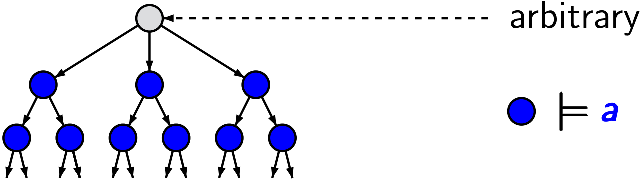
both formulas require computation trees of the form:



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wrong,

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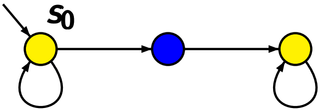

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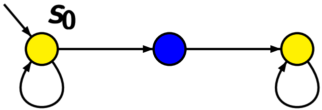

$s_0 \not\models \exists\bigcirc\exists\Box a$

Correct or wrong?

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correct.

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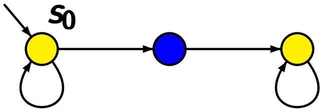

$s_0 \not\models \exists\bigcirc\exists\Box a$

note: $Sat(\exists\Box a) = \varnothing$

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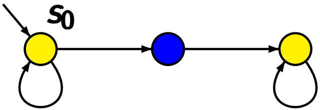

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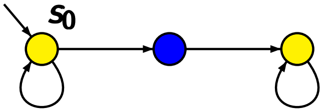

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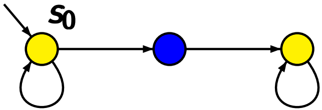

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$s_0 \models \exists\Box\exists\bigcirc a$

$s_0 \models \exists\bigcirc a$

$\Longrightarrow \quad s_0\, s_0\, s_0 \ldots \models \Box\exists\bigcirc a$

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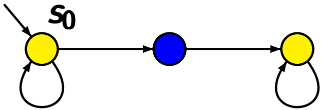
correct.

$\exists\bigcirc\exists\Box a \equiv \exists\Box\exists\bigcirc a$

wrong, e.g.,



$s_0 \not\models \exists\bigcirc\exists\Box a$

$s_0 \models \exists\Box\exists\bigcirc a$

$$s_0 \models \exists\bigcirc a$$

$$\Longrightarrow \quad s_0\, s_0\, s_0 \ldots \models \Box\exists\bigcirc a$$

$$\Longrightarrow \quad s_0 \models \exists\Box\exists\bigcirc a$$

Weak until W

Weak until W

in **LTL**: $\varphi \, \mathsf{W} \, \psi \stackrel{\text{def}}{=} (\varphi \, \mathsf{U} \, \psi) \vee \Box\varphi$

in **CTL**: **?**

Weak until W

in **LTL**: $\varphi \, \mathsf{W} \, \psi \overset{\text{def}}{=} (\varphi \, \mathsf{U} \, \psi) \lor \Box\varphi$

duality of **U** and **W**:

$$\neg(\varphi \, \mathsf{U} \, \psi) \equiv (\varphi \land \neg\psi) \, \mathsf{W} \, (\neg\varphi \land \neg\psi)$$

$$\neg(\varphi \, \mathsf{W} \, \psi) \equiv (\varphi \land \neg\psi) \, \mathsf{U} \, (\neg\varphi \land \neg\psi)$$

in **CTL**: **?**

Weak until W

in **LTL**: $\varphi \, \mathbf{W} \, \psi \stackrel{\text{def}}{=} (\varphi \, \mathbf{U} \, \psi) \vee \Box\varphi$

duality of **U** and **W**:

$$\neg(\varphi \, \mathbf{U} \, \psi) \equiv (\varphi \wedge \neg\psi) \, \mathbf{W} \, (\neg\varphi \wedge \neg\psi)$$

$$\neg(\varphi \, \mathbf{W} \, \psi) \equiv (\varphi \wedge \neg\psi) \, \mathbf{U} \, (\neg\varphi \wedge \neg\psi)$$

definition of **W** in **CTL** on the basis of duality rules:

$$\exists(\Phi \, \mathbf{W} \, \Psi) \stackrel{\text{def}}{=} \neg\forall((\Phi \wedge \neg\Psi) \, \mathbf{U} \, (\neg\Phi \wedge \neg\Psi))$$

Weak until W

in **LTL**: $\varphi \, \mathsf{W} \, \psi \overset{\text{def}}{=} (\varphi \, \mathsf{U} \, \psi) \vee \Box\varphi$

duality of **U** and **W**:

$$\neg(\varphi \, \mathsf{U} \, \psi) \equiv (\varphi \wedge \neg\psi) \, \mathsf{W} \, (\neg\varphi \wedge \neg\psi)$$

$$\neg(\varphi \, \mathsf{W} \, \psi) \equiv (\varphi \wedge \neg\psi) \, \mathsf{U} \, (\neg\varphi \wedge \neg\psi)$$

definition of **W** in **CTL** on the basis of duality rules:

$$\exists(\Phi \, \mathsf{W} \, \Psi) \overset{\text{def}}{=} \neg\forall((\Phi \wedge \neg\Psi) \, \mathsf{U} \, (\neg\Phi \wedge \neg\Psi))$$

$$\forall(\Phi \, \mathsf{W} \, \Psi) \overset{\text{def}}{=} \neg\exists((\Phi \wedge \neg\Psi) \, \mathsf{U} \, (\neg\Phi \wedge \neg\Psi))$$

Weak until W in CTL

definition of **W** in **CTL** on the basis of duality rules:

$$\exists(\Phi \, \mathsf{W} \, \Psi) \stackrel{\text{def}}{=} \neg\forall\big((\Phi \wedge \neg\Psi) \, \mathsf{U} \, (\neg\Phi \wedge \neg\Psi) \big)$$

$$\forall(\Phi \, \mathsf{W} \, \Psi) \stackrel{\text{def}}{=} \neg\exists\big((\Phi \wedge \neg\Psi) \, \mathsf{U} \, (\neg\Phi \wedge \neg\Psi) \big)$$

Weak until W in CTL

definition of **W** in **CTL** on the basis of duality rules:

$$\exists(\Phi \, \mathsf{W} \, \Psi) \overset{\text{def}}{=} \neg\forall\big((\Phi \wedge \neg\Psi) \, \mathsf{U} \, (\neg\Phi \wedge \neg\Psi)\big)$$

$$\forall(\Phi \, \mathsf{W} \, \Psi) \overset{\text{def}}{=} \neg\exists\big((\Phi \wedge \neg\Psi) \, \mathsf{U} \, (\neg\Phi \wedge \neg\Psi)\big)$$

note that:

$$\exists(\Phi \, \mathsf{W} \, \Psi) \equiv \exists(\Phi \, \mathsf{U} \, \Psi) \vee \exists\Box\Phi$$

Weak until W in CTL

definition of **W** in **CTL** on the basis of duality rules:

$$\exists(\Phi \, W \, \Psi) \overset{\text{def}}{=} \neg\forall((\Phi \wedge \neg\Psi) \, U \, (\neg\Phi \wedge \neg\Psi))$$

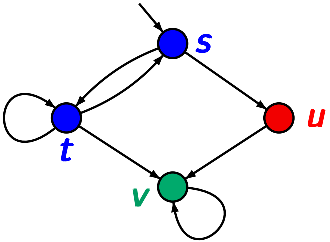
$$\forall(\Phi \, W \, \Psi) \overset{\text{def}}{=} \neg\exists((\Phi \wedge \neg\Psi) \, U \, (\neg\Phi \wedge \neg\Psi))$$

note that:

$$\exists(\Phi \, W \, \Psi) \equiv \exists(\Phi \, U \, \Psi) \vee \exists\Box\Phi$$

$$\forall(\Phi \, W \, \Psi) \not\equiv \forall(\Phi \, U \, \Psi) \vee \forall\Box\Phi$$

Weak until W in CTL



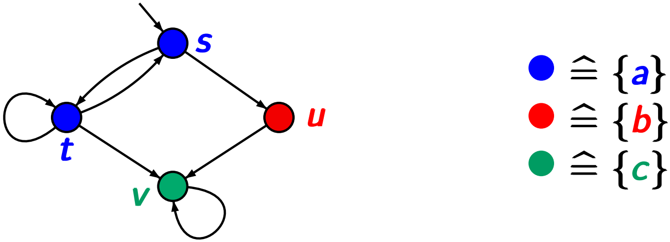
$\bullet \widehat{=} \{a\}$

$\bullet \widehat{=} \{b\}$

$\bullet \widehat{=} \{c\}$

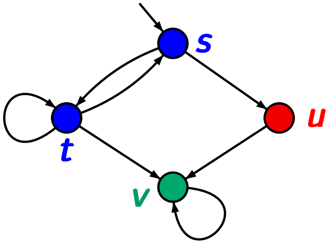
$\mathcal{T} \models \forall\Diamond\exists(a \text{ W } c)$ **?**

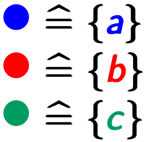
Weak until W in CTL



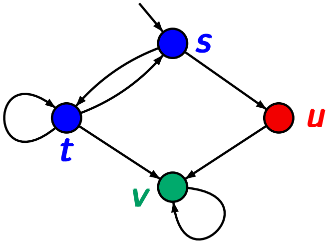
$\mathcal{T} \models \forall\Diamond\exists(a \mathsf{W} c)$ $\surd$ as $s \models \exists(a \mathsf{W} c)$

Weak until W in CTL





$\mathcal{T} \models \forall\Diamond\exists(a \; \mathsf{W} \; c)$ $\surd$ as $s\, s_1\, s_2 \ldots \models \Diamond\exists(a \; \mathsf{W} \; c)$

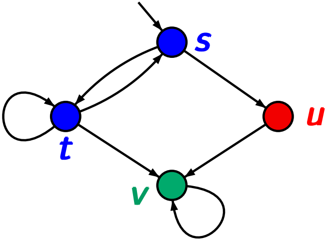


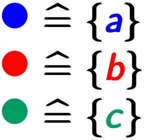
● $\widehat{=}$ $\{a\}$
● $\widehat{=}$ $\{b\}$
● $\widehat{=}$ $\{c\}$

$\mathcal{T} \models \forall\Diamond\exists(a \mathsf{W} c)$ √ as $s \models \exists(a \mathsf{W} c)$

$\mathcal{T} \models \exists(a \mathsf{W} \exists\Box b)$?

Weak until W in CTL

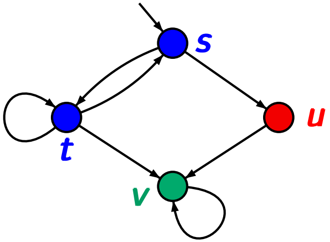




$\mathcal{T} \models \forall\Diamond\exists(a \;\mathsf{W}\; c)$ $\surd$ as $s \models \exists(a \;\mathsf{W}\; c)$

$\mathcal{T} \models \exists(a \;\mathsf{W}\; \exists\Box b)$ $\surd$ as $s \models \exists\Box a$

Weak until W in CTL



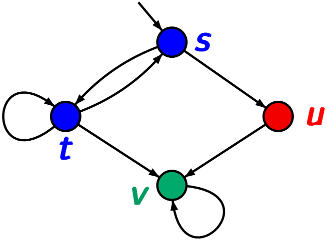
● $\widehat{=}$ $\{a\}$
● $\widehat{=}$ $\{b\}$
● $\widehat{=}$ $\{c\}$

$\mathcal{T} \models \forall\Diamond\exists(a \,\mathsf{W}\, c)$ √ as $s \models \exists(a \,\mathsf{W}\, c)$

$\mathcal{T} \models \exists(a \,\mathsf{W}\, \exists\Box b)$ √ as $s \models \exists\Box a$

$\mathcal{T} \models \forall((\exists\bigcirc(b \vee c)) \,\mathsf{W}\, (a \wedge b))$ **?**

Weak until W in CTL



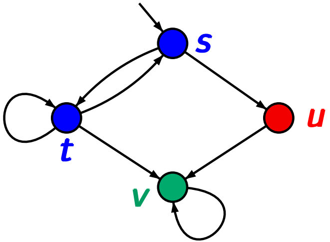
● $\widehat{=}$ $\{a\}$
● $\widehat{=}$ $\{b\}$
● $\widehat{=}$ $\{c\}$

$\mathcal{T} \models \forall\Diamond\exists(a \mathsf{W} c)$ ✓ as $s \models \exists(a \mathsf{W} c)$

$\mathcal{T} \models \exists(a \mathsf{W} \exists\Box b)$ ✓ as $s \models \exists\Box a$

$\mathcal{T} \models \forall((\exists\bigcirc(b \vee c)) \mathsf{W} (a \wedge b))$ ✓

Weak until W in CTL



● $\widehat{=}$ $\{a\}$
● $\widehat{=}$ $\{b\}$
● $\widehat{=}$ $\{c\}$

$\mathcal{T} \models \forall\Diamond\exists(a \mathsf{W} c)$ $\surd$ as $s \models \exists(a \mathsf{W} c)$

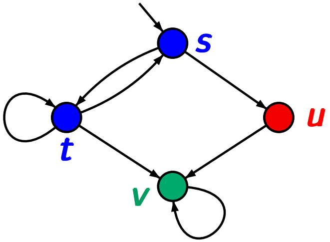
$\mathcal{T} \models \exists(a \mathsf{W} \exists\Box b)$ $\surd$ as $s \models \exists\Box a$

$\mathcal{T} \models \forall((\exists\bigcirc(b \vee c)) \mathsf{W} (a \wedge b))$ $\surd$

$\uparrow$

three types of paths: $(s\,t)^\omega$ or $(s\,t)^+ v^\omega$ or $(s\,t)^* s\,u\,v^\omega$

Weak until W in CTL



$\bullet \; \widehat{=} \; \{a\}$ (blue)
$\bullet \; \widehat{=} \; \{b\}$ (red)
$\bullet \; \widehat{=} \; \{c\}$ (green)

$\mathcal{T} \models \forall\Diamond\exists(a \,\mathsf{W}\, c)$ $\surd$ as $s \models \exists(a \,\mathsf{W}\, c)$

$\mathcal{T} \models \exists(a \,\mathsf{W}\, \exists\Box b)$ $\surd$ as $s \models \exists\Box a$

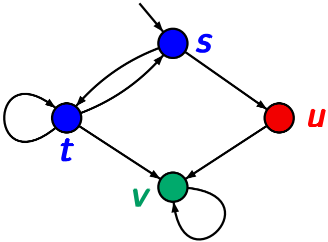
$\mathcal{T} \models \forall((\exists\bigcirc(b \vee c)) \,\mathsf{W}\, (a \wedge b))$ $\surd$

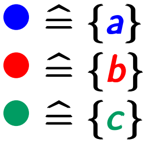
↑

three types of paths: $(s\,t)^\omega$ or $(s\,t)^+\,v^\omega$ or $(s\,t)^*\,s\,u\,v^\omega$

in all three cases: $\pi \models \Box\exists\bigcirc(b \vee c)$

Weak until W in CTL

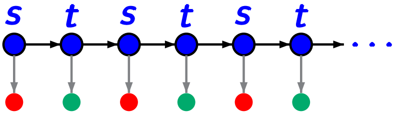




$\mathcal{T} \models \forall\Diamond\exists(a \ \mathsf{W} \ c)$ $\surd$ as $s \models \exists(a \ \mathsf{W} \ c)$

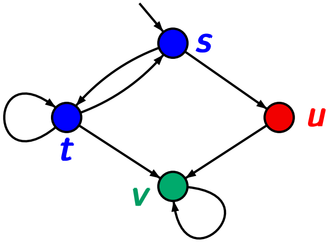
$\mathcal{T} \models \exists(a \ \mathsf{W} \ \exists\Box b)$ $\surd$ as $s \models \exists\Box a$

$\mathcal{T} \models \forall((\exists\bigcirc(b \vee c)) \ \mathsf{W} \ (a \wedge b))$ $\surd$



$\models \Box\exists\bigcirc(b \vee c)$

Weak until W in CTL

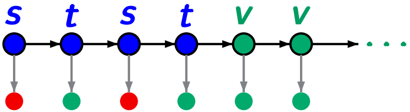


● $\widehat{=}$ $\{a\}$
● $\widehat{=}$ $\{b\}$
● $\widehat{=}$ $\{c\}$

$\mathcal{T} \models \forall\Diamond\exists(a \, \mathsf{W} \, c)$ √ as $s \models \exists(a \, \mathsf{W} \, c)$

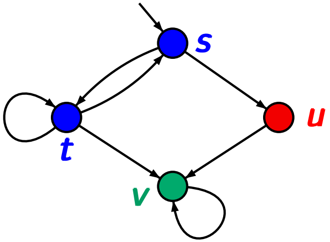
$\mathcal{T} \models \exists(a \, \mathsf{W} \, \exists\Box b)$ √ as $s \models \exists\Box a$

$\mathcal{T} \models \forall((\exists\bigcirc(b \vee c)) \, \mathsf{W} \, (a \wedge b))$ √



$\models \Box\exists\bigcirc(b \vee c)$

Weak until W in CTL

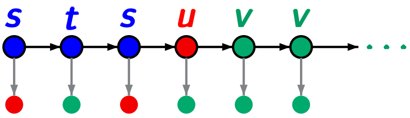


$\bullet \mathrel{\widehat{=}} \{a\}$ (blue)
$\bullet \mathrel{\widehat{=}} \{b\}$ (red)
$\bullet \mathrel{\widehat{=}} \{c\}$ (green)

$\mathcal{T} \models \forall\Diamond\exists(a \mathsf{W} c)$ √ as $s \models \exists(a \mathsf{W} c)$

$\mathcal{T} \models \exists(a \mathsf{W} \exists\Box b)$ √ as $s \models \exists\Box a$

$\mathcal{T} \models \forall((\exists\bigcirc(b \vee c)) \mathsf{W} (a \wedge b))$ √



$\models \Box\exists\bigcirc(b \vee c)$

Expansion laws

Expansion laws

$$\exists(\Phi \, \mathsf{U} \, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \, \mathsf{U} \, \Psi))$$

Expansion laws

$$\exists(\Phi \mathsf{U} \Psi) \equiv \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \mathsf{U} \Psi))$$

$$\forall(\Phi \mathsf{U} \Psi) \equiv ?$$

Expansion laws

$$\exists(\Phi \, \mathsf{U} \, \Psi) \equiv \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \, \mathsf{U} \, \Psi))$$

$$\forall(\Phi \, \mathsf{U} \, \Psi) \equiv \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \, \mathsf{U} \, \Psi))$$

Expansion laws

$$\exists(\Phi \, \mathsf{U} \, \Psi) \equiv \Psi \vee (\Phi \wedge \exists \bigcirc \exists(\Phi \, \mathsf{U} \, \Psi))$$

$$\forall(\Phi \, \mathsf{U} \, \Psi) \equiv \Psi \vee (\Phi \wedge \forall \bigcirc \forall(\Phi \, \mathsf{U} \, \Psi))$$

$$\exists \Diamond \Psi \equiv \Psi \vee \exists \bigcirc \exists \Diamond \Psi$$

$$\forall \Diamond \Psi \equiv \Psi \vee \forall \bigcirc \forall \Diamond \Psi$$

Expansion laws

$$\exists(\Phi \,\mathsf{U}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \,\mathsf{U}\, \Psi))$$

$$\forall(\Phi \,\mathsf{U}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \,\mathsf{U}\, \Psi))$$

$$\exists\Diamond\Psi \;\equiv\; \Psi \vee \exists\bigcirc\exists\Diamond\Psi$$

$$\forall\Diamond\Psi \;\equiv\; \Psi \vee \forall\bigcirc\forall\Diamond\Psi$$

$$\exists(\Phi \,\mathsf{W}\, \Psi) \;\equiv$$

Expansion laws

$$\exists(\Phi \,\mathsf{U}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \,\mathsf{U}\, \Psi))$$

$$\forall(\Phi \,\mathsf{U}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \,\mathsf{U}\, \Psi))$$

$$\exists\Diamond\Psi \;\equiv\; \Psi \vee \exists\bigcirc\exists\Diamond\Psi$$

$$\forall\Diamond\Psi \;\equiv\; \Psi \vee \forall\bigcirc\forall\Diamond\Psi$$

$$\exists(\Phi \,\mathsf{W}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \,\mathsf{W}\, \Psi))$$

Expansion laws

$$\exists(\Phi \mathsf{U} \Psi) \equiv \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \mathsf{U} \Psi))$$

$$\forall(\Phi \mathsf{U} \Psi) \equiv \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \mathsf{U} \Psi))$$

$$\exists\Diamond\Psi \equiv \Psi \vee \exists\bigcirc\exists\Diamond\Psi$$

$$\forall\Diamond\Psi \equiv \Psi \vee \forall\bigcirc\forall\Diamond\Psi$$

$$\exists(\Phi \mathsf{W} \Psi) \equiv \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \mathsf{W} \Psi))$$

$$\forall(\Phi \mathsf{W} \Psi) \equiv \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \mathsf{W} \Psi))$$

Expansion laws

$$\exists(\Phi \, \mathsf{U} \, \Psi) \equiv \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \, \mathsf{U} \, \Psi))$$

$$\forall(\Phi \, \mathsf{U} \, \Psi) \equiv \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \, \mathsf{U} \, \Psi))$$

$$\exists\Diamond\Psi \equiv \Psi \vee \exists\bigcirc\exists\Diamond\Psi$$

$$\forall\Diamond\Psi \equiv \Psi \vee \forall\bigcirc\forall\Diamond\Psi$$

$$\exists(\Phi \, \mathsf{W} \, \Psi) \equiv \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \, \mathsf{W} \, \Psi))$$

$$\forall(\Phi \, \mathsf{W} \, \Psi) \equiv \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \, \mathsf{W} \, \Psi))$$

$$\exists\Box\Phi \equiv ?$$

Expansion laws

$$\exists(\Phi \,\mathsf{U}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \,\mathsf{U}\, \Psi))$$

$$\forall(\Phi \,\mathsf{U}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \,\mathsf{U}\, \Psi))$$

$$\exists\Diamond\Psi \;\equiv\; \Psi \vee \exists\bigcirc\exists\Diamond\Psi$$

$$\forall\Diamond\Psi \;\equiv\; \Psi \vee \forall\bigcirc\forall\Diamond\Psi$$

$$\exists(\Phi \,\mathsf{W}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \,\mathsf{W}\, \Psi))$$

$$\forall(\Phi \,\mathsf{W}\, \Psi) \;\equiv\; \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \,\mathsf{W}\, \Psi))$$

$$\exists\Box\Phi \;\equiv\; \Phi \wedge \exists\bigcirc\exists\Box\Phi$$

Expansion laws

$$\exists(\Phi \, \mathsf{U} \, \Psi) \equiv \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \, \mathsf{U} \, \Psi))$$

$$\forall(\Phi \, \mathsf{U} \, \Psi) \equiv \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \, \mathsf{U} \, \Psi))$$

$$\exists\Diamond\Psi \equiv \Psi \vee \exists\bigcirc\exists\Diamond\Psi$$

$$\forall\Diamond\Psi \equiv \Psi \vee \forall\bigcirc\forall\Diamond\Psi$$

$$\exists(\Phi \, \mathsf{W} \, \Psi) \equiv \Psi \vee (\Phi \wedge \exists\bigcirc\exists(\Phi \, \mathsf{W} \, \Psi))$$

$$\forall(\Phi \, \mathsf{W} \, \Psi) \equiv \Psi \vee (\Phi \wedge \forall\bigcirc\forall(\Phi \, \mathsf{W} \, \Psi))$$

$$\exists\Box\Phi \equiv \Phi \wedge \exists\bigcirc\exists\Box\Phi$$

$$\forall\Box\Phi \equiv \Phi \wedge \forall\bigcirc\forall\Box\Phi$$

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \quad \equiv \quad \neg\exists\Diamond\neg\Phi$$

$$\forall\Diamond\Phi \quad \equiv \quad \neg\exists\Box\neg\Phi$$

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \equiv \neg\exists\Diamond\neg\Phi$$

$$\forall\Diamond\Phi \equiv \neg\exists\Box\neg\Phi$$

self-duality of $\bigcirc$:

$$\forall\bigcirc\Phi \equiv \neg\exists\bigcirc\neg\Phi$$

$$\exists\bigcirc\Phi \equiv \neg\forall\bigcirc\neg\Phi$$

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \equiv \neg\exists\Diamond\neg\Phi$$

$$\forall\Diamond\Phi \equiv \neg\exists\Box\neg\Phi$$

self-duality of $\bigcirc$:

$$\forall\bigcirc\Phi \equiv \neg\exists\bigcirc\neg\Phi$$

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duality of **U** and **W**, e.g.:

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \equiv \neg\exists\Diamond\neg\Phi$$

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self-duality of $\bigcirc$:

$$\forall\bigcirc\Phi \equiv \neg\exists\bigcirc\neg\Phi$$

$$\exists\bigcirc\Phi \equiv \neg\forall\bigcirc\neg\Phi$$

duality of **U** and **W**, e.g.:

$$\forall(\Phi \,\mathbf{U}\, \Psi)$$

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \equiv \neg\exists\Diamond\neg\Phi$$

$$\forall\Diamond\Phi \equiv \neg\exists\Box\neg\Phi$$

self-duality of $\bigcirc$:

$$\forall\bigcirc\Phi \equiv \neg\exists\bigcirc\neg\Phi$$

$$\exists\bigcirc\Phi \equiv \neg\forall\bigcirc\neg\Phi$$

duality of **U** and **W**, e.g.:

$$\forall(\Phi \,\mathsf{U}\, \Psi) \equiv \neg\exists((\Phi \wedge \neg\Psi) \,\mathsf{W}\, (\neg\Phi \wedge \neg\Psi))$$

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \equiv \neg\exists\Diamond\neg\Phi$$

$$\forall\Diamond\Phi \equiv \neg\exists\Box\neg\Phi$$

self-duality of $\bigcirc$:

$$\forall\bigcirc\Phi \equiv \neg\exists\bigcirc\neg\Phi$$

$$\exists\bigcirc\Phi \equiv \neg\forall\bigcirc\neg\Phi$$

duality of **U** and **W**, e.g.:

$$\forall(\Phi \,\mathsf{U}\, \Psi) \equiv \neg\exists((\Phi \wedge \neg\Psi) \,\mathsf{W}\, (\neg\Phi \wedge \neg\Psi))$$

$$\equiv \neg\exists((\neg\Psi) \,\mathsf{W}\, (\neg\Phi \wedge \neg\Psi))$$

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \equiv \neg\exists\Diamond\neg\Phi$$

$$\forall\Diamond\Phi \equiv \neg\exists\Box\neg\Phi$$

self-duality of $\bigcirc$:

$$\forall\bigcirc\Phi \equiv \neg\exists\bigcirc\neg\Phi$$

$$\exists\bigcirc\Phi \equiv \neg\forall\bigcirc\neg\Phi$$

duality of **U** and **W**, e.g.:

$$\begin{aligned} \forall(\Phi \, \mathsf{U} \, \Psi) &\equiv \neg\exists((\Phi \wedge \neg\Psi) \, \mathsf{W} \, (\neg\Phi \wedge \neg\Psi)) \\ &\equiv \neg\exists((\neg\Psi) \, \mathsf{W} \, (\neg\Phi \wedge \neg\Psi)) \\ &\equiv \neg\exists((\neg\Psi) \, \mathsf{U} (\neg\Phi \wedge \neg\Psi)) \;\wedge\; \neg\exists\Box\neg\Psi \end{aligned}$$

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \equiv \neg\exists\Diamond\neg\Phi$$

$$\forall\Diamond\Phi \equiv \neg\exists\Box\neg\Phi$$

self-duality of $\bigcirc$:

$$\forall\bigcirc\Phi \equiv \neg\exists\bigcirc\neg\Phi$$

$$\exists\bigcirc\Phi \equiv \neg\forall\bigcirc\neg\Phi$$

duality of **U** and **W** yields

$$\forall(\Phi \,\mathsf{U}\, \Psi) \equiv \neg\exists((\neg\Psi)\,\mathsf{U}(\neg\Phi \wedge \neg\Psi)) \wedge \neg\exists\Box\neg\Psi$$

Duality laws

duality of $\Box$ and $\Diamond$:

$$\forall\Box\Phi \equiv \neg\exists\Diamond\neg\Phi$$

$$\forall\Diamond\Phi \equiv \neg\exists\Box\neg\Phi$$

self-duality of $\bigcirc$:

$$\forall\bigcirc\Phi \equiv \neg\exists\bigcirc\neg\Phi$$

$$\exists\bigcirc\Phi \equiv \neg\forall\bigcirc\neg\Phi$$

derivation of $\forall\mathsf{U}$ from $\exists\mathsf{U}$ and $\exists\Box$:

$$\forall(\Phi\,\mathsf{U}\,\Psi) \equiv \neg\exists((\neg\Psi)\,\mathsf{U}(\neg\Phi\wedge\neg\Psi)) \wedge \neg\exists\Box\neg\Psi$$

$\forall\mathsf{U}$ and $\forall\bigcirc$ are expressible via $\exists\mathsf{U}$, $\exists\bigcirc$ and $\exists\Box$

Existential normalform for CTL

For each **CTL** formula Ψ there is an equivalent **CTL** formula Φ built by

- operators of propositional logic
- the modalities $\exists\bigcirc$, $\exists\mathbf{U}$ and $\exists\Box$.

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transformation $\Psi \rightsquigarrow \Phi$ relies on:

$$\forall\bigcirc\Psi \rightsquigarrow \neg\exists\bigcirc\neg\Psi$$

$$\forall(\Psi_1 \,\mathsf{U}\, \Psi_2) \rightsquigarrow \neg\exists(\neg\Psi_2 \,\mathsf{U}(\neg\Psi_1 \wedge \neg\Psi_2)) \wedge \neg\exists\Box\neg\Psi_2$$

Example: ∃-normal form for CTL formula

CTL formula $\rightsquigarrow$ CTL formula in ∃-normal form

$$\forall\bigcirc\Psi \rightsquigarrow \neg\exists\bigcirc\neg\Psi$$

$$\forall(\Psi_1 \,\mathsf{U}\, \Psi_2) \rightsquigarrow \neg\exists(\neg\Psi_2 \,\mathsf{U}(\neg\Psi_1 \wedge \neg\Psi_2)) \wedge \neg\exists\Box\neg\Psi_2$$

$$\forall((\forall\bigcirc a) \,\mathsf{U}\, \neg c)$$

Example: ∃-normal form for CTL formula

CTL formula $\rightsquigarrow$ CTL formula in ∃-normal form

$$\forall \bigcirc \Psi \rightsquigarrow \neg \exists \bigcirc \neg \Psi$$

$$\forall (\Psi_1 \mathsf{U} \Psi_2) \rightsquigarrow \neg \exists (\neg \Psi_2 \mathsf{U} (\neg \Psi_1 \wedge \neg \Psi_2)) \wedge \neg \exists \Box \neg \Psi_2$$

$$\forall ((\forall \bigcirc a) \mathsf{U} \neg c)$$

$$\equiv \neg \exists (\neg \neg c \mathsf{U} ((\neg \forall \bigcirc a) \wedge \neg \neg c)) \wedge \neg \exists \Box \neg \neg c$$

Example: ∃-normal form for CTL formula

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$$\forall(\Psi_1 \,\mathsf{U}\, \Psi_2) \rightsquigarrow \neg\exists(\neg\Psi_2 \,\mathsf{U}(\neg\Psi_1 \wedge \neg\Psi_2)) \wedge \neg\exists\Box\neg\Psi_2$$

$$\forall((\forall\bigcirc a) \,\mathsf{U}\, \neg c)$$

$$\equiv \quad \neg\exists(\neg\neg c \,\mathsf{U}((\neg\forall\bigcirc a) \wedge \neg\neg c)) \quad \wedge \quad \neg\exists\Box\neg\neg c$$

$$\equiv \quad \neg\exists(c \,\mathsf{U}((\neg\forall\bigcirc a) \wedge c)) \quad \wedge \quad \neg\exists\Box c$$

Example: ∃-normal form for CTL formula

CTL formula	$\rightsquigarrow$	CTL formula in ∃-normal form
$\forall\bigcirc\Psi$	$\rightsquigarrow$	$\neg\exists\bigcirc\neg\Psi$
$\forall(\Psi_1 \mathsf{U} \Psi_2)$	$\rightsquigarrow$	$\neg\exists(\neg\Psi_2 \mathsf{U}(\neg\Psi_1 \wedge \neg\Psi_2)) \wedge \neg\exists\Box\neg\Psi_2$

$$\forall((\forall\bigcirc a) \mathsf{U} \neg c)$$

$$\equiv \quad \neg\exists(\neg\neg c \,\mathsf{U}((\neg\forall\bigcirc a) \wedge \neg\neg c)) \quad \wedge \quad \neg\exists\Box\neg\neg c$$

$$\equiv \quad \neg\exists(c \,\mathsf{U}((\neg\forall\bigcirc a) \wedge c)) \quad \wedge \quad \neg\exists\Box c$$

$$\equiv \quad \neg\exists(c \,\mathsf{U}((\exists\bigcirc\neg a) \wedge c)) \quad \wedge \quad \neg\exists\Box c$$

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but no additional operator for $\bigcirc$ required syntax of **CTL** formulas in **PNF**:

state formulas:

$$\Phi \;::=\; \mathit{true} \;\big|\; \mathit{false} \;\big|\; a \;\big|\; \neg a \;\big|\; \Phi_1 \wedge \Phi_2 \;\big|\; \Phi_1 \vee \Phi_2 \;\big|\; \exists\varphi \;\big|\; \forall\varphi$$

path formulas:

$$\varphi \;::=\; \bigcirc\Phi \;\big|\; \Phi_1 \,\mathsf{U}\, \Phi_2 \;\big|\; \Phi_1 \,\mathsf{W}\, \Phi_2$$

syntax of **CTL** formulas in **PNF**:

state formulas:

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path formulas:

$$\varphi ::= \bigcirc\Phi \mid \Phi_1 \, \mathsf{U} \, \Phi_2 \mid \Phi_1 \, \mathsf{W} \, \Phi_2$$

For each **CTL** formula Ψ there is an equivalent **CTL** formula Φ in **PNF**

CTL $\rightsquigarrow$ CTL-PNF

CTL formula $\rightsquigarrow$ CTL formula in PNF

CTL formula $\leadsto$ CTL formula in PNF

$\neg$*true* $\leadsto$ *false*

CTL formula $\rightsquigarrow$ CTL formula in PNF

$\neg \mathit{true} \rightsquigarrow \mathit{false}$

$\neg(\Phi_1 \wedge \Phi_2) \rightsquigarrow \neg\Phi_1 \vee \neg\Phi_2$ de Morgan laws

CTL formula $\rightsquigarrow$ CTL formula in PNF

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$\neg\exists(\Phi_1 \,\mathsf{U}\, \Phi_2) \rightsquigarrow \forall((\cancel{\Phi_1} \wedge \neg\Phi_2) \,\mathsf{W}\, (\neg\Phi_1 \wedge \neg\Phi_2))$

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$$\neg\exists(\Phi_1 \,\mathsf{U}\, \Phi_2) \rightsquigarrow \forall(\neg\Phi_2 \,\mathsf{W}\, (\neg\Phi_1 \wedge \neg\Phi_2))$$

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$$\neg\forall(\Phi_1 \mathsf{U} \Phi_2) \rightsquigarrow \exists(\neg\Phi_2 \mathsf{W} (\neg\Phi_1 \wedge \neg\Phi_2))$$

... exponential blowup possible ...