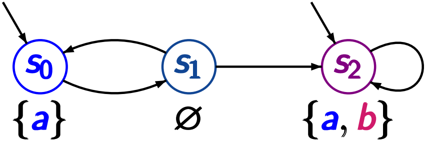
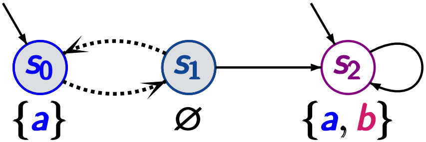
Correct or wrong ?



$AP = \{a, b\}$

path $\pi = s_0\, s_1\, s_0\, s_1\, s_0\, s_1\, \ldots$

Correct or wrong ?



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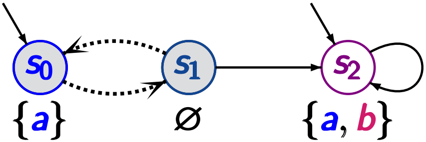

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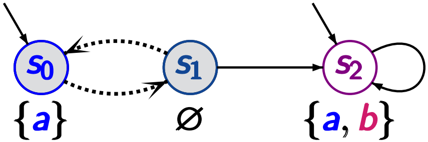
$trace(\pi) = (\{a\}\, \varnothing)^\omega$

$\pi \models a \,\mathsf{U}\, b$?

Correct or wrong ?



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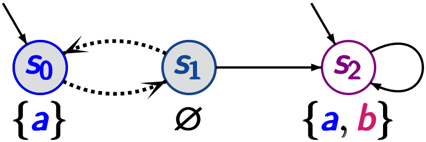
path $\pi = s_0\, s_1\, s_0\, s_1\, s_0\, s_1\, \ldots$ $\qquad$ $trace(\pi) = (\{a\}\, \varnothing)^\omega$

$\pi \not\models a \,\mathsf{U}\, b$ $\qquad$ as $s_0 \not\models b$ and $s_1 \not\models a \vee b$

Correct or wrong ?



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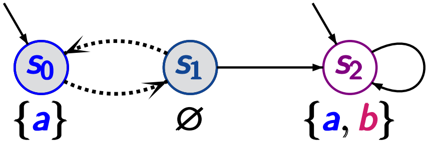
$\pi \models \Diamond b \rightarrow (a \,\mathsf{U}\, b)$?

Correct or wrong ?



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$\pi \not\models a \,\mathsf{U}\, b$ $\quad$ as $s_0 \not\models b$ and $s_1 \not\models a \vee b$

$\pi \models \Diamond b \rightarrow (a \,\mathsf{U}\, b)$ $\quad$ as $\pi \not\models \Diamond b$

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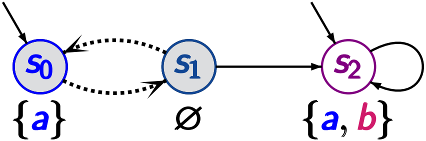

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path $\pi = s_0\, s_1\, s_0\, s_1\, s_0\, s_1\, \ldots$ $\qquad$ $trace(\pi) = (\{a\}\, \varnothing)^\omega$

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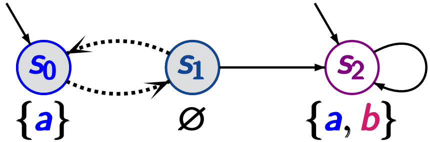
$\pi \models \bigcirc \bigcirc \neg b$?



$AP = \{a, b\}$

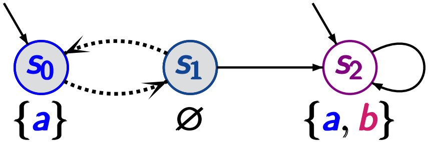
path $\pi = s_0\, s_1\, s_0\, s_1\, s_0\, s_1\, \ldots$ $\qquad trace(\pi) = (\{a\}\, \varnothing)^\omega$

$\pi \not\models a \, \mathsf{U} \, b$ $\qquad$ as $s_0 \not\models b$ and $s_1 \not\models a \vee b$

$\pi \models \Diamond b \rightarrow (a \, \mathsf{U} \, b)$ $\qquad$ as $\pi \not\models \Diamond b$

$\pi \models \bigcirc \bigcirc \neg b$ $\qquad$ as $s_0 \models \neg b$

Correct or wrong ?



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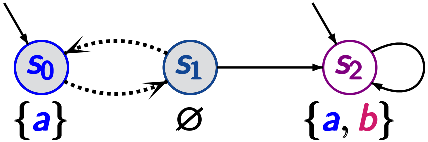
$\pi \models \bigcirc \bigcirc \neg b$ $\qquad$ as $s_0 \models \neg b$

$\pi \models \Box a$?

Correct or wrong ?



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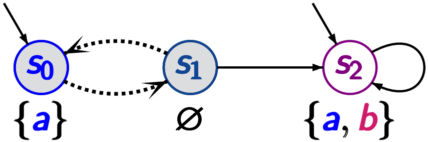
$\pi \not\models \Box a$ $\quad$ as $s_1 \not\models a$

Correct or wrong ?



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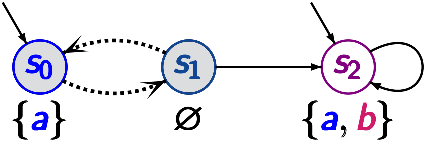
$\pi \models \Box\Diamond a$?

Correct or wrong ?



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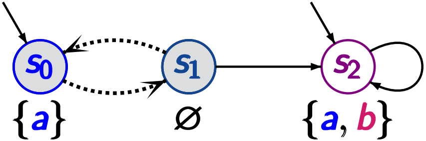
$\pi \not\models \Box a$ $\qquad$ as $s_1 \not\models a$

$\pi \models \Box\Diamond a$ $\qquad$ as $\Box\Diamond \,\widehat{=}\,$ infinitely often

Correct or wrong ?



$AP = \{a, b\}$

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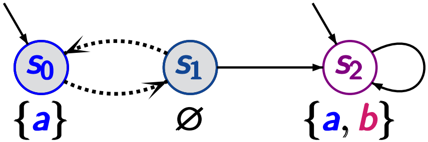
$\pi \models \Box\Diamond a$ $\qquad$ as $\Box\Diamond \mathrel{\widehat{=}}$ infinitely often

$\pi \models \Diamond\Box a$?



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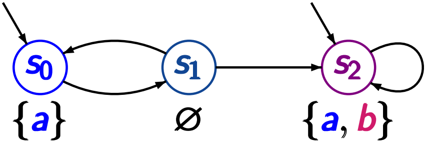
$\pi \not\models \Diamond\Box a$ $\qquad$ as $\Diamond\Box \mathrel{\widehat{=}}$ eventually forever

Which formulas hold for $\mathcal{T}$?



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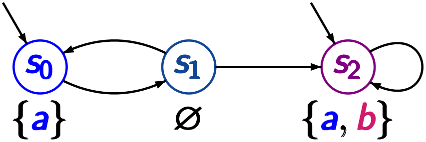

$AP = \{a, b\}$

$\mathcal{T} \models a$

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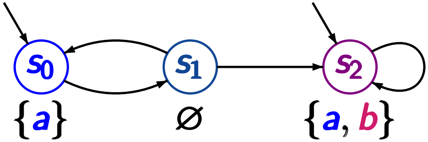

$AP = \{a, b\}$

$\mathcal{T} \models a$ as $s_0 \models a$ and $s_2 \models a$

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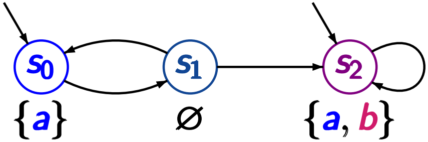

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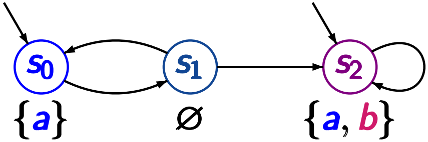

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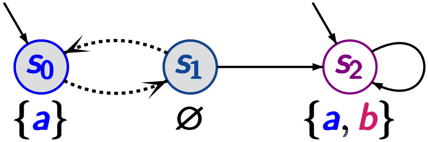

$AP = \{a, b\}$

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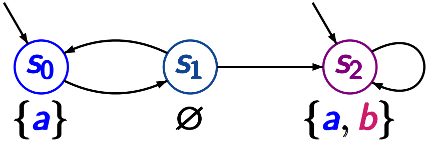

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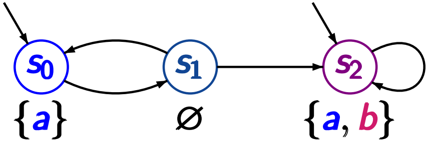

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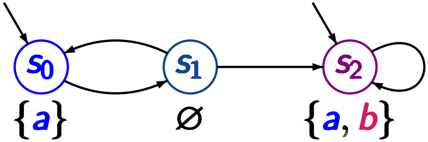

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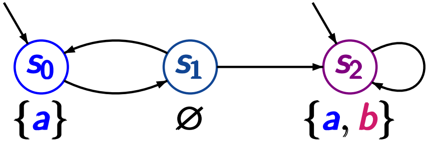

$AP = \{a, b\}$

$\mathcal{T} \models a$ as $s_0 \models a$ and $s_2 \models a$

$\mathcal{T} \not\models \Diamond\Box a$ as $s_0\, s_1\, s_0\, s_1 \ldots \not\models \Diamond\Box a$

$\mathcal{T} \models \Diamond\Box b \vee \Box\Diamond(\neg a \wedge \neg b)$ as $s_2 \models b$, $s_1 \not\models a, b$

$\mathcal{T} \models \Box(a \rightarrow (\bigcirc\neg a \vee b))$ as $s_2 \models b$, $s_0 \models \bigcirc\neg a$

Correct or wrong?

For each path π we have: $\pi \models \varphi$ or $\pi \models \neg\varphi$

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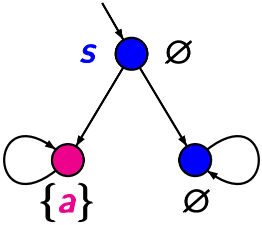

$s \not\models \Diamond a$ and $s \not\models \neg\Diamond a$

LTL-formulas for MUTEX protocols

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LTL formulas over $AP = \{wait_1, crit_1, wait_2, crit_2\}$

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$$\varphi_{mutex} = \textbf{?}$$

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LTL-formulas for MUTEX protocols

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- "every process enters the critical section infinitely often"

$$\varphi_{live} \;=\; \textbf{?}$$

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$$\varphi_{live} = \Box\Diamond crit_1 \wedge \Box\Diamond crit_2$$

- starvation freedom
  "every waiting process finally enters its critical section"

$$\varphi_{sf} = \textbf{?}$$

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- "every process enters the critical section infinitely often"

$$\varphi_{live} = \Box\Diamond crit_1 \wedge \Box\Diamond crit_2$$

- starvation freedom
  "every waiting process finally enters its critical section"

$$\varphi_{sf} = \Box(wait_1 \rightarrow \Diamond crit_1) \wedge \Box(wait_2 \rightarrow \Diamond crit_2)$$

Provide an LTL formula over $AP = \{a, b\}$ for ...

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- set of all words $A_0\, A_1\, A_2 \ldots \in \left(2^{AP}\right)^{\omega}$ such that:

$$\forall i \geqslant 0. \; (\; a \in A_i \implies i \geqslant 1 \wedge b \in A_{i-1} \;)$$

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$$\widehat{=} \; Words\big(\, \Box(b \vee \bigcirc \neg a) \, \big)$$

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- set of all words of the form

$$\{b\}^{n_1}\,\{a\}\,\{b\}^{n_2}\,\{a\}\,\{b\}^{n_3}\,\{a\}\ldots$$

where $n_1, n_2, n_3, \ldots \geqslant 0$

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$$\widehat{=}\ \ Words(\ \Box((b \wedge \neg a)\ \mathsf{U}\ (a \wedge \neg b))\ )$$

Correct or wrong?

$$\Diamond(\varphi \vee \psi) \equiv \Diamond\varphi \vee \Diamond\psi$$

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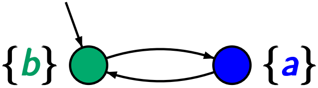
correct

$$\Diamond(\varphi \wedge \psi) \equiv \Diamond\varphi \wedge \Diamond\psi$$

wrong,
e.g.,



$\models \Diamond b \wedge \Diamond a$

$\not\models \Diamond(b \wedge a)$

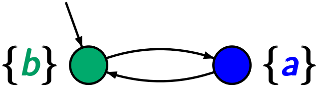
Correct or wrong?

$$\Diamond(\varphi \vee \psi) \equiv \Diamond\varphi \vee \Diamond\psi$$

correct

$$\Diamond(\varphi \wedge \psi) \equiv \Diamond\varphi \wedge \Diamond\psi$$

wrong,
e.g.,



$\models \Diamond b \wedge \Diamond a$

$\not\models \Diamond(b \wedge a)$

---

similarly: $\Box(\varphi \wedge \psi) \equiv \Box\varphi \wedge \Box\psi$

$\Box(\varphi \vee \psi) \not\equiv \Box\varphi \vee \Box\psi$

Correct or wrong?

$$\Diamond\Diamond\varphi \equiv \Diamond\varphi$$

Correct or wrong?

$\Diamond\Diamond\varphi \equiv \Diamond\varphi$

correct

	$\exists k \geqslant 0 \;\; \exists j \geqslant k$ s.t. $A_j\, A_{j+1}\, A_{j+2} \ldots \models \varphi$
iff	$\exists j \geqslant 0$ s.t. $A_j\, A_{j+1}\, A_{j+2} \ldots \models \varphi$

Correct or wrong?

$\Diamond\Diamond\varphi \equiv \Diamond\varphi$

correct analogously: $\Box\Box\varphi \equiv \Box\varphi$

$$\exists k \geqslant 0 \;\; \exists j \geqslant k \;\; \text{s.t. } A_j A_{j+1} A_{j+2} \ldots \models \varphi$$

iff $$\exists j \geqslant 0 \;\; \text{s.t. } A_j A_{j+1} A_{j+2} \ldots \models \varphi$$

$$\forall k \geqslant 0 \;\; \forall j \geqslant k \;\; \text{s.t. } A_j A_{j+1} A_{j+2} \ldots \models \varphi$$

iff $$\forall j \geqslant 0 \;\; \text{s.t. } A_j A_{j+1} A_{j+2} \ldots \models \varphi$$

Correct or wrong?

$\Diamond\Diamond\varphi \equiv \Diamond\varphi$

correct analogously: $\Box\Box\varphi \equiv \Box\varphi$

$\bigcirc\Box\varphi \equiv \Box\bigcirc\varphi$

Correct or wrong?

$\Diamond\Diamond\varphi \equiv \Diamond\varphi$

correct analogously: $\Box\Box\varphi \equiv \Box\varphi$

$\bigcirc\Box\varphi \equiv \Box\bigcirc\varphi$

correct

Correct or wrong?

$\Diamond\Diamond\varphi \equiv \Diamond\varphi$

correct analogously: $\Box\Box\varphi \equiv \Box\varphi$

$\bigcirc\Box\varphi \equiv \Box\bigcirc\varphi \stackrel{\text{def}}{=} \psi$

correct

note that:

$A_0\, A_1\, A_2 \ldots \models \psi$ iff $A_i\, A_{i+1} \ldots \models \varphi$ for all $i \geqslant 1$

Correct or wrong?

$\Diamond\Diamond\varphi \equiv \Diamond\varphi$

correct analogously: $\Box\Box\varphi \equiv \Box\varphi$

$\bigcirc\Box\varphi \equiv \Box\bigcirc\varphi$

correct

$\Diamond\Box\varphi \equiv \Box\Diamond\varphi$

Correct or wrong?

$\Diamond\Diamond\varphi \equiv \Diamond\varphi$

correct analogously: $\Box\Box\varphi \equiv \Box\varphi$

$\bigcirc\Box\varphi \equiv \Box\bigcirc\varphi$

correct

$\Diamond\Box\varphi \equiv \Box\Diamond\varphi$

$\Box\Diamond \;\widehat{=}\;$ infinitely often

$\Diamond\Box \;\widehat{=}\;$ eventually forever

Correct or wrong?

$\Diamond\Diamond\varphi \equiv \Diamond\varphi$

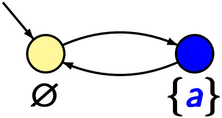
correct analogously: $\Box\Box\varphi \equiv \Box\varphi$

$\bigcirc\Box\varphi \equiv \Box\bigcirc\varphi$

correct

$\Diamond\Box\varphi \equiv \Box\Diamond\varphi$

wrong



$\Box\Diamond \;\hat{=}\;$ infinitely often

$\Diamond\Box \;\hat{=}\;$ eventually forever

$\models \Box\Diamond a$

$\not\models \Diamond\Box a$

The weak until operator W

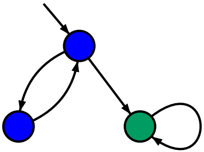
$$\varphi \, \mathsf{W} \, \psi \;\stackrel{\text{def}}{=}\; (\varphi \, \mathsf{U} \, \psi) \vee \Box\varphi$$

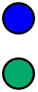
deriving "always" and "until" from "weak until":

$$\Box\varphi \equiv \varphi \, \mathsf{W} \, \mathit{false}$$

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

Does $\mathcal{T} \models a \, \mathsf{W} \, b$ hold ?

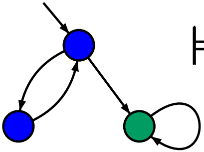




$\widehat{=} \ \{a\}$

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

Does $\mathcal{T} \models a \, \mathsf{W} \, b$ hold ?

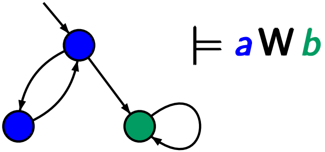


$\models a \, \mathsf{W} \, b$

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

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

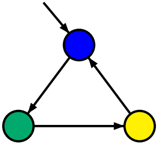
Does $\mathcal{T} \models a \,\mathsf{W}\, b$ hold ?



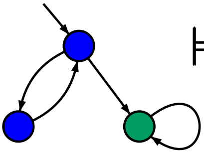
● $\widehat{=}$ $\{a\}$

● $\widehat{=}$ $\{b\}$

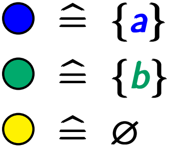
● $\widehat{=}$ $\varnothing$

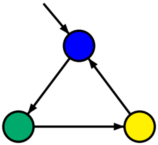


Does $\mathcal{T} \models a \, \mathsf{W} \, b$ hold ?



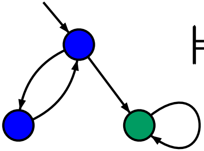
$\models a \, \mathsf{W} \, b$



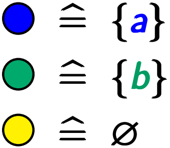


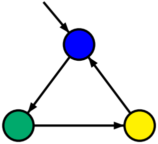
$\models \; a \, \mathsf{W} \, b \quad$ (even $a \, \mathsf{U} \, b$)

Does $\mathcal{T} \models a \,\mathsf{W}\, b$ hold ?

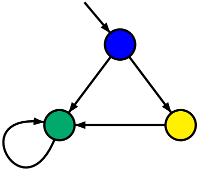


$\models a \,\mathsf{W}\, b$

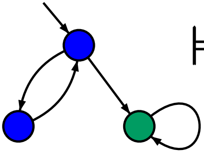




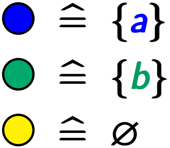
$\models a \,\mathsf{W}\, b$ (even $a \,\mathsf{U}\, b$)

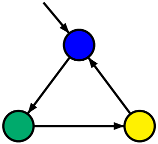


Does $\mathcal{T} \models a \mathsf{W} b$ hold ?

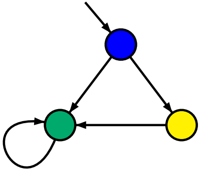


$\models a \mathsf{W} b$



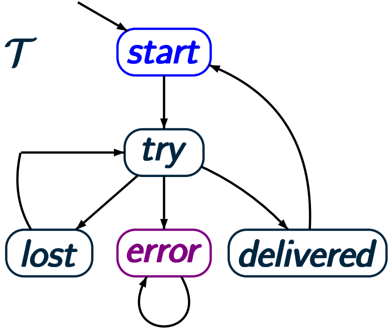


$\models a \mathsf{W} b$ (even $a \mathsf{U} b$)



$\not\models a \mathsf{W} b$

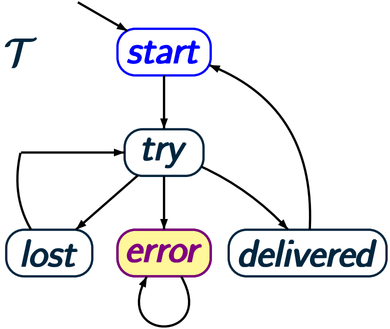
Example: CTL semantics



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

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

Example: CTL semantics

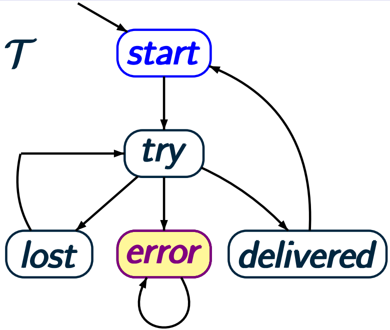


$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$?

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

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

Example: CTL semantics



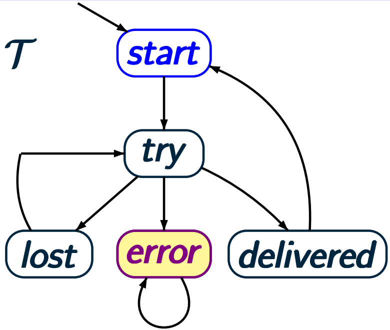
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$?

$\Phi_1 = \exists\Diamond\, \forall\Box\, \neg start \;\rightsquigarrow\; \exists\Diamond\; error$

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

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

Example: CTL semantics



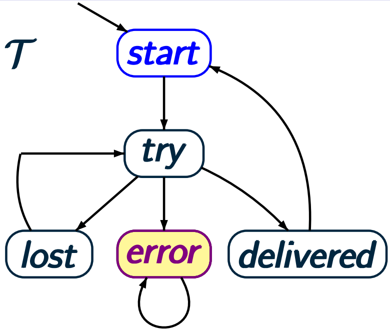
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$?

$$\Phi_1 = \exists\Diamond\, \forall\Box\, \neg start \;\rightsquigarrow\; \exists\Diamond\; error$$

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

$$Sat(\exists\Diamond\forall\Box\neg start) = Sat(\exists\Diamond error) = \text{“all states”}$$

Example: CTL semantics



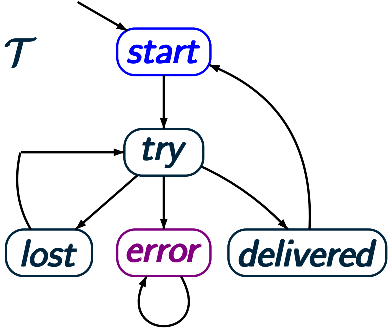
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$ ✓

$\Phi_1 = \exists\Diamond\, \forall\Box\, \neg start \;\rightsquigarrow\; \exists\Diamond\; error$

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

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

Example: CTL semantics

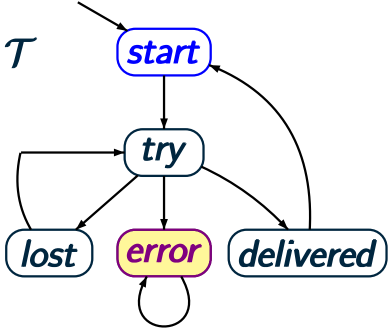


$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

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

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

Example: CTL semantics



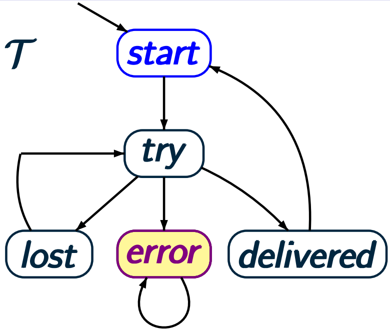
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

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

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

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

Example: CTL semantics



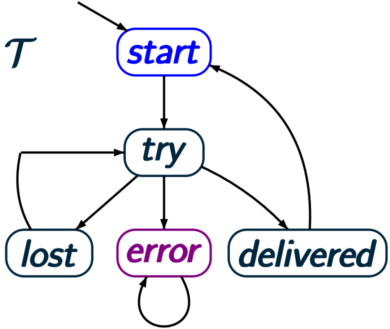
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

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

$\Phi_2 = \forall\bigcirc\ \exists\bigcirc\ \forall\Box\ \neg start \quad \rightsquigarrow \quad \forall\bigcirc\ \exists\bigcirc\ error$

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

Example: CTL semantics



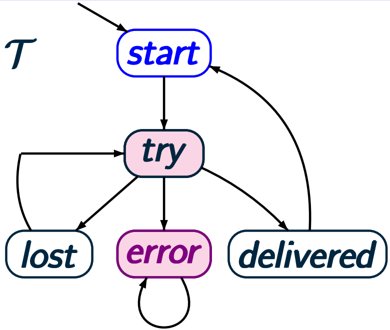
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

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

$\Phi_2 = \forall\bigcirc\ \exists\bigcirc\ \forall\Box\ \neg start \quad \leadsto \quad \forall\bigcirc\ \exists\bigcirc\ error$

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

Example: CTL semantics



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

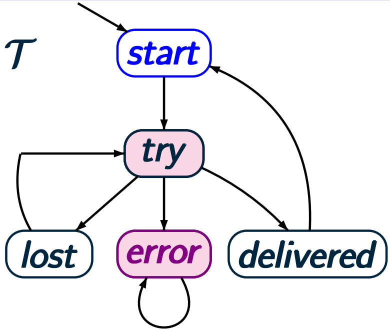
$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$ **?**

$\Phi_2 = \forall\bigcirc\ \exists\bigcirc\ \forall\Box\ \neg start \quad \rightsquigarrow \quad \forall\bigcirc\ \exists\bigcirc\ error$

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

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

Example: CTL semantics



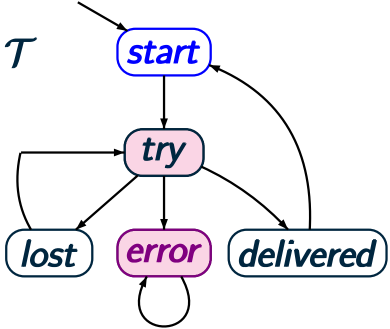
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

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

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

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

Example: CTL semantics



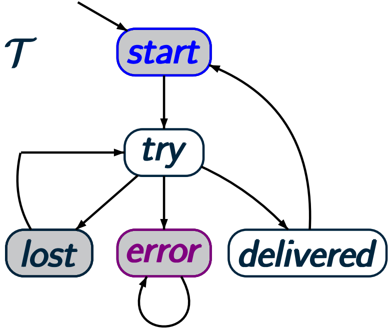
$\mathcal{T} \models \exists\Diamond\forall\Box\neg start$

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

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

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

Example: CTL semantics



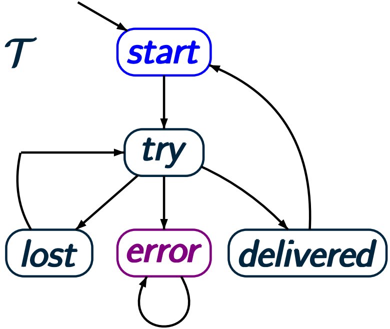
$\mathcal{T} \not\models \exists\Diamond\forall\Box\neg start$

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

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

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

Example: CTL semantics



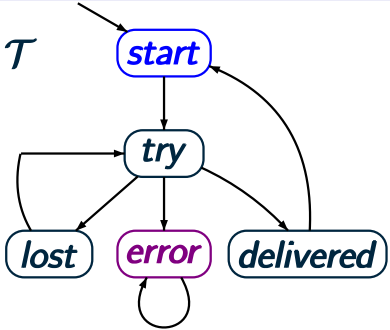
$\mathcal{T} \models \exists\Diamond\forall\Box\neg$*start*

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



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

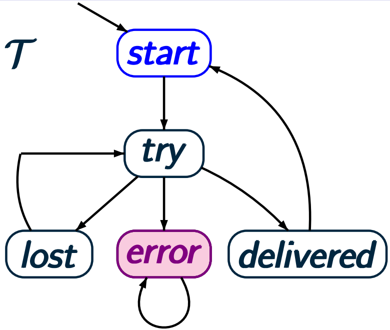
$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

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

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

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

Example: CTL semantics



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

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

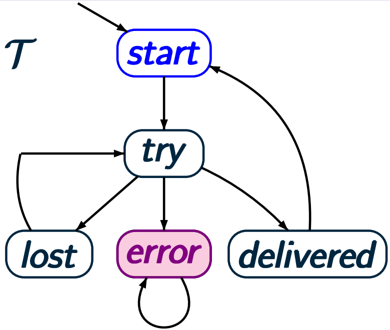
$\mathcal{T} \models \exists\bigcirc\forall\bigcirc\forall\Box\neg start$ **?**

$$\Phi_3 = \exists\bigcirc \; \forall\bigcirc \; \forall\Box \; \neg start \;\; \rightsquigarrow \;\; \exists\bigcirc \; \forall\bigcirc error$$

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

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

Example: CTL semantics



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

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

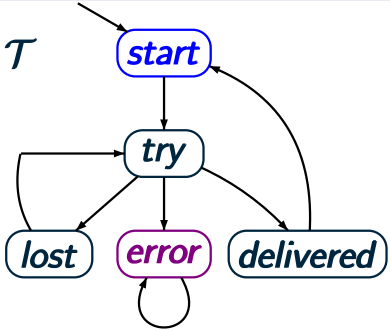
$\mathcal{T} \models \exists\bigcirc\forall\bigcirc\forall\Box\neg start$?

$$\Phi_3 = \exists\bigcirc\ \forall\bigcirc\ \forall\Box\ \neg start \quad \rightsquigarrow \quad \exists\bigcirc\ error$$

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

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

Example: CTL semantics



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

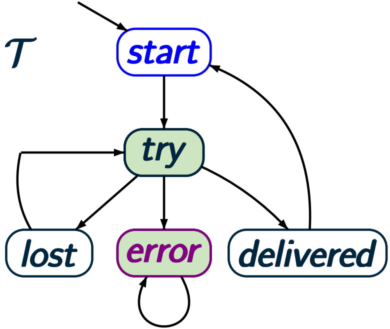
$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

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

$\Phi_3 \;=\; \exists\bigcirc\;\forall\bigcirc\;\forall\Box\;\neg start \quad \rightsquigarrow \quad \exists\bigcirc\; error$

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

Example: CTL semantics



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

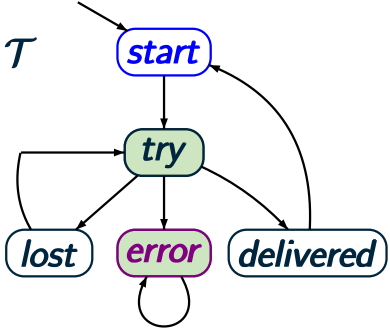
$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

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

$$\Phi_3 = \exists\bigcirc\ \forall\bigcirc\ \forall\Box\ \neg start \quad \rightsquigarrow \quad \exists\bigcirc\ error$$

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

Example: CTL semantics



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

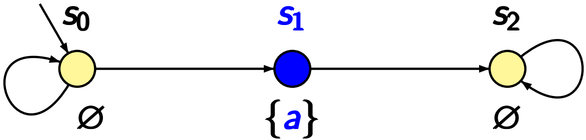
$\mathcal{T} \models \forall\bigcirc\exists\bigcirc\forall\Box\neg start$

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

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

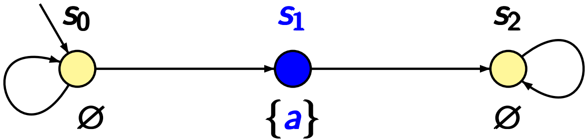
$$Sat(\forall\Box\neg start) = \{error\}$$
$$Sat(\forall\bigcirc\forall\Box\neg start) = \{error\}$$
$$Sat(\exists\bigcirc\forall\bigcirc\forall\Box\neg start) = \{error, try\}$$

Example: CTL semantics



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

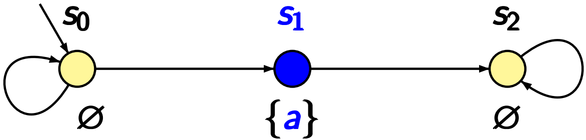
Example: CTL semantics



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

answer: no

Example: CTL semantics

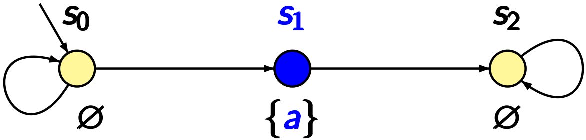


does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

answer: no

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

Example: CTL semantics

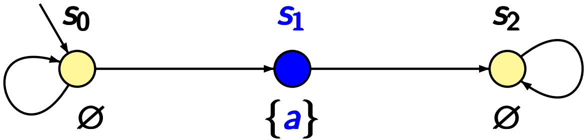


does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

answer: no

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

Example: CTL semantics

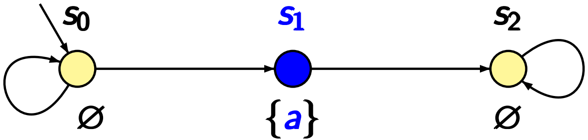


does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

answer: no

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

Example: CTL semantics



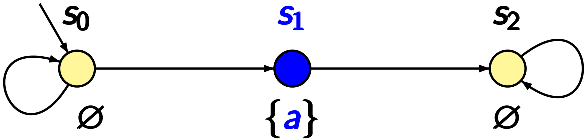
does $\mathcal{T} \models \exists\bigcirc\forall\Box\neg a$ hold ?

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 ?

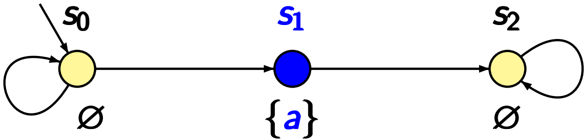
answer: no

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 ?

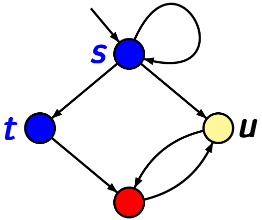
answer: no

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

answer: yes

$$
\begin{aligned}
Sat(\exists\bigcirc\neg a) &= \{s_0, s_1, s_2\} \\
Sat(\forall\Box\exists\bigcirc\neg a) &= \{s_0, s_1, s_2\}
\end{aligned}
$$

Example: CTL semantics



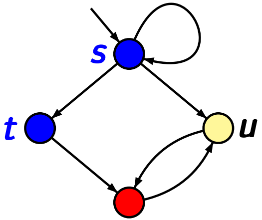
blue $\widehat{=} \{a\}$

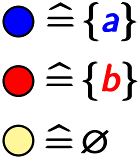
red $\widehat{=} \{b\}$

yellow $\widehat{=} \varnothing$

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

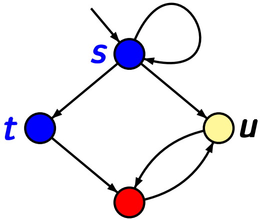
Example: CTL semantics

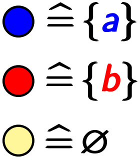




$\mathcal{T} \models \exists\Box\exists(a \, \mathsf{U} \, b)$ $\quad\surd$ as $s \models \exists(a \, \mathsf{U} \, b)$

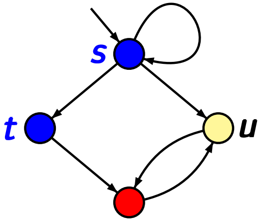
Example: CTL semantics

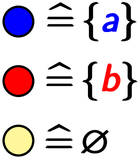




$\mathcal{T} \models \exists\Box\exists(a \, \mathsf{U} \, b)$ $\quad\surd\quad$ as $s\,s\,s\,\ldots \models \Box\exists(a \, \mathsf{U} \, b)$

Example: CTL semantics

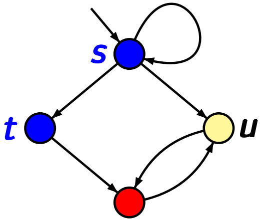




$\mathcal{T} \models \exists\Box\exists(a \,\mathsf{U}\, b)$ $\quad\surd\quad$ as $s\,s\,s\,\ldots \models \Box\exists(a \,\mathsf{U}\, b)$

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

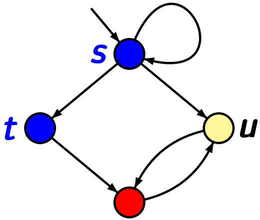
Example: CTL semantics

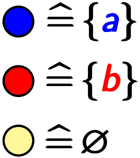


$\mathcal{T} \models \exists\Box\exists(a \,\mathsf{U}\, b)$ ✓ as $s\,s\,s \ldots \models \Box\exists(a \,\mathsf{U}\, b)$

$\mathcal{T} \not\models \exists((\exists\bigcirc a) \,\mathsf{U}\, b)$ as $t \not\models \exists\bigcirc a$, $u \not\models \exists\bigcirc a$

Example: CTL semantics



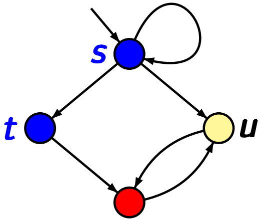


$\mathcal{T} \models \exists\Box\exists(a \,\mathsf{U}\, b)$ $\sqrt{}$ as $s\,s\,s\,\ldots \models \Box\exists(a \,\mathsf{U}\, b)$

$\mathcal{T} \not\models \exists((\exists\bigcirc a) \,\mathsf{U}\, b)$ as $t \not\models \exists\bigcirc a$, $u \not\models \exists\bigcirc a$

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

Example: CTL semantics



blue $\widehat{=} \{a\}$

red $\widehat{=} \{b\}$

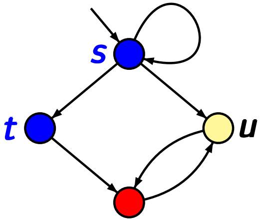
yellow $\widehat{=} \varnothing$

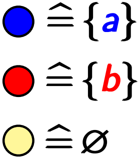
$\mathcal{T} \models \exists\Box\exists(a \,\mathsf{U}\, b)$ ✓ as $s\,s\,s \ldots \models \Box\exists(a \,\mathsf{U}\, b)$

$\mathcal{T} \not\models \exists((\exists\bigcirc a) \,\mathsf{U}\, b)$ as $t \not\models \exists\bigcirc a$, $u \not\models \exists\bigcirc a$

$\mathcal{T} \models \exists(a \,\mathsf{U}\, \forall(\neg a \,\mathsf{U}\, b))$ ✓

Example: CTL semantics

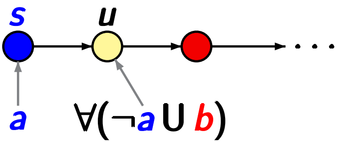




$\mathcal{T} \models \exists\Box\exists(a \,\mathsf{U}\, b)$ ✓ as $s\,s\,s\,\ldots \models \Box\exists(a \,\mathsf{U}\, b)$

$\mathcal{T} \not\models \exists((\exists\bigcirc a) \,\mathsf{U}\, b)$ as $t \not\models \exists\bigcirc a$, $u \not\models \exists\bigcirc a$

$\mathcal{T} \models \exists(a \,\mathsf{U}\, \forall(\neg a \,\mathsf{U}\, b))$ ✓



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

Correct or wrong?

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

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

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answer: no

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

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

answer: no

$\mathcal{T} \models \Phi$ iff $s_0 \models \Phi$ for all initial states s_0

Correct or wrong?

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

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

answer: no

$\mathcal{T} \models \Phi$	iff	$s_0 \models \Phi$ for all initial states s_0
$\mathcal{T} \not\models \neg\Phi$	iff	there exists an initial state s_0 with $s_0 \not\models \neg\Phi$

Correct or wrong?

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

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

answer: no

$\mathcal{T} \models \Phi$ iff $s_0 \models \Phi$ for all initial states s_0

$\mathcal{T} \not\models \neg\Phi$ iff there exists an initial state s_0 with $s_0 \not\models \neg\Phi$

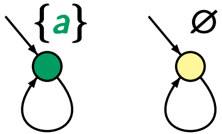
iff there exists an initial state s_0 with $s_0 \models \Phi$

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

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

answer: no

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



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

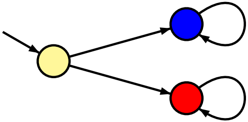
$\mathcal{T} \not\models \neg\exists\Box a$

Correct or wrong?

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

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

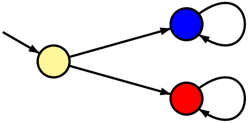
wrong, e.g,



Correct or wrong?

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

wrong, e.g,

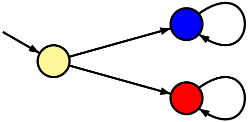


$$\forall\Diamond(a \wedge b) \;\equiv\; \forall\Diamond a \wedge \forall\Diamond b$$

Correct or wrong?

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

wrong, e.g,



$\forall\Diamond(a \wedge b) \;\equiv\; \forall\Diamond a \wedge \forall\Diamond b$

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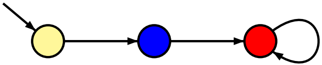

Correct or wrong?

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

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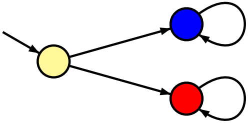
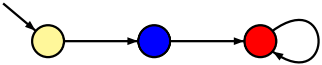


$$\forall\Diamond(a \wedge b) \;\equiv\; \forall\Diamond a \wedge \forall\Diamond b$$

wrong, e.g.,



but:

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

Correct or wrong?

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

Correct or wrong?

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

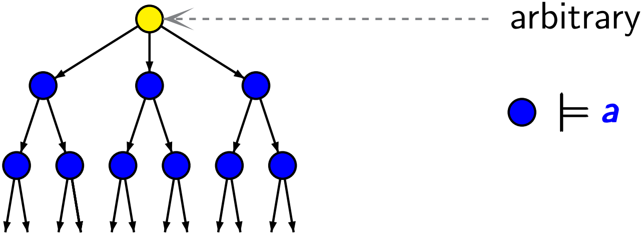
correct.

Correct or wrong?

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

correct.

both formulas require computation trees of the form:



Correct or wrong?

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

correct.

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

Correct or wrong?

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

correct.

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

wrong,

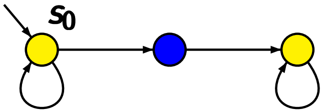
Correct or wrong?

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

correct.

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

wrong, e.g.,



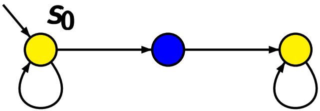
Correct or wrong?

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

correct.

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

wrong, e.g.,



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

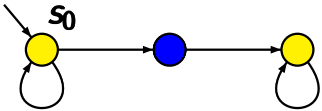
Correct or wrong?

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

correct.

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

wrong, e.g.,



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

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

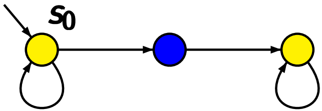
Correct or wrong?

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

correct.

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

wrong, e.g.,



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

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

Correct or wrong?

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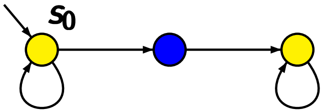


$s_0 \not\models \exists\bigcirc\exists\Box a$

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

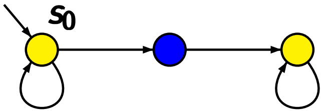
$s_0 \models \exists\bigcirc a$

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

correct.

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

wrong, e.g.,



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

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

$s_0 \models \exists\bigcirc a$

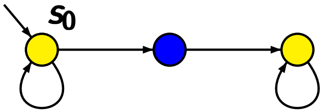
$\Longrightarrow \quad s_0\, s_0\, s_0 \ldots \models \Box\exists\bigcirc a$

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

correct.

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

wrong, e.g.,



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

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

$s_0 \models \exists\bigcirc a$

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

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

Does $\forall\Diamond(a \wedge \exists\bigcirc a) \equiv \Diamond(a \wedge \bigcirc a)$ hold ?

CTL vs LTL

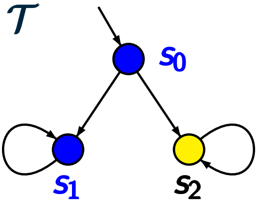
Does $\forall\Diamond(a \wedge \exists\bigcirc a) \equiv \Diamond(a \wedge \bigcirc a)$ hold ?

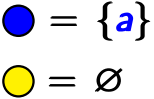
answer: **no.**

CTL vs LTL

Does $\forall\Diamond(a \wedge \exists\bigcirc a) \equiv \Diamond(a \wedge \bigcirc a)$ hold ?

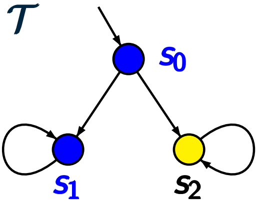
answer: **no.**





Does $\forall\Diamond(a \wedge \exists\bigcirc a) \equiv \Diamond(a \wedge \bigcirc a)$ hold ?

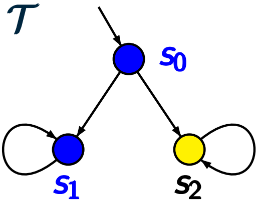
answer: **no.**



$\mathcal{T} \not\models \Diamond(a \wedge \bigcirc a)$

Does $\forall\Diamond(a \wedge \exists\bigcirc a) \equiv \Diamond(a \wedge \bigcirc a)$ hold ?

answer: **no.**



$\mathcal{T} \not\models \Diamond(a \wedge \bigcirc a)$

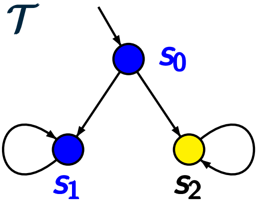
note: $\pi = s_0\, s_2\, s_2\, s_2 \ldots$ is a path in $\mathcal{T}$ with

$trace(\pi) = \{a\}\, \varnothing\, \varnothing\, \varnothing \ldots \notin Words(\Diamond(a \wedge \bigcirc a))$

CTL vs LTL

Does $\forall\Diamond(a \wedge \exists\bigcirc a) \equiv \Diamond(a \wedge \bigcirc a)$ hold ?

answer: **no.**



$\mathcal{T} \not\models \Diamond(a \wedge \bigcirc a)$

$\mathcal{T} \models \forall\Diamond(a \wedge \exists\bigcirc a)$

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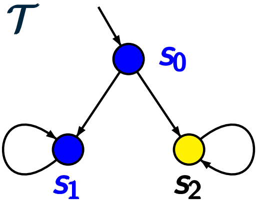

$\mathcal{T} \not\models \Diamond(a \wedge \bigcirc a)$

$\mathcal{T} \models \forall\Diamond(a \wedge \exists\bigcirc a)$

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

$$Sat(\forall\Diamond(a \wedge \exists\bigcirc a)) = \{s_0, s_1\}$$

Correct or wrong?

$s \models \exists\Box\exists\Diamond a$ iff there is a path $\pi \in \mathit{Paths}(s)$ with $\pi \models \Box\Diamond a$

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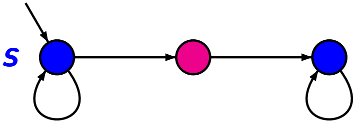

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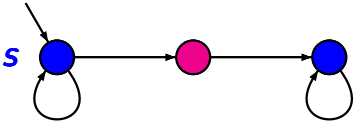

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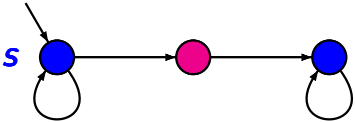

$s \models \exists\Box\exists\Diamond a$

note that: $s \not\models \exists\Diamond a$

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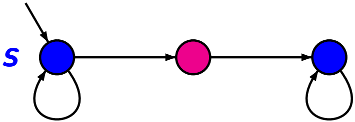


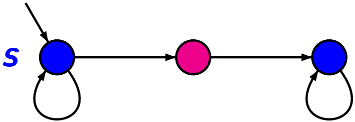
$s \models \exists\Box\exists\Diamond a$

note that: $s \models \exists\Diamond a$

thus: $s\,s\,s\,\ldots \models \Box\exists\Diamond a$

$s \models \exists\Box\exists\Diamond a$ iff there is a path $\pi \in Paths(s)$ with $\pi \models \Box\Diamond a$

wrong.



$s \models \exists\Box\exists\Diamond a$

note that: $s \models \exists\Diamond a$

thus: $s\,s\,s\ldots \models \Box\exists\Diamond a$

but there is no path where $\Box\Diamond a$ holds

Correct or wrong?

If $\mathcal{T}_1$ and $\mathcal{T}_2$ are trace equivalent TS then for all **CTL** formulas Φ: $\mathcal{T}_1 \models \Phi$ iff $\mathcal{T}_2 \models \Phi$

Correct or wrong?

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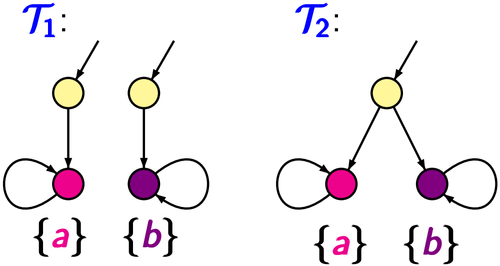

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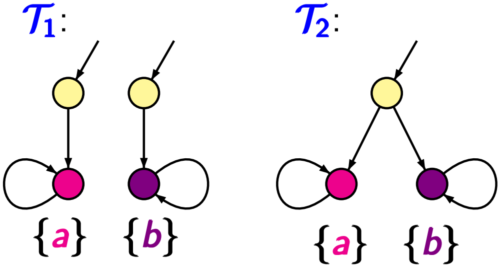
wrong.



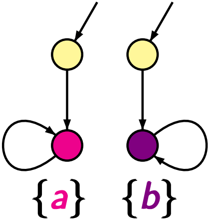
$\mathcal{T}_1$ and $\mathcal{T}_2$ are trace equivalent

Correct or wrong?

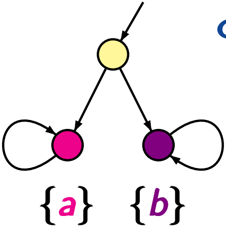
If $\mathcal{T}_1$ and $\mathcal{T}_2$ are trace equivalent TS then for all **CTL** formulas Φ: $\mathcal{T}_1 \models \Phi$ iff $\mathcal{T}_2 \models \Phi$

wrong.

$\mathcal{T}_1$:



$\mathcal{T}_2$:



consider the CTL formula

$\Phi = \exists\bigcirc a \wedge \exists\bigcirc b$

$\mathcal{T}_1 \not\models \Phi$

$\mathcal{T}_2 \models \Phi$

$\mathcal{T}_1$ and $\mathcal{T}_2$ are trace equivalent