Formal Methods for Software Development

Temporal Model Checking (part 2) + First-Order Logic

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28th September 2018

Part I

Finishing Temporal Model Checking

Model Checking

Check whether a formula is valid in all runs of a transition system.

Given a transition system $\mathcal{T}$ (e.g., derived from a PROMELA program).

Verification task: is the LTL formula ϕ satisfied in all traces of $\mathcal{T}$, i.e.,

$$\mathcal{T} \models \phi \quad ?$$

LTL Model Checking—Overview

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What Remains?

last lecture

3.–5. product of transition system and Büchi automaton (construction and analysis)

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this lecture

2. generalised Büchi automata and their normalisation
1. translating LTL into generalised Büchi automata

Generalised Büchi Automata $\mathcal{GB}$ and Translation to (normal) Büchi Automata $\mathcal{B}$

Generalised Büchi Automata

A generalised Büchi automaton is defined as:

$$\mathcal{GB} = (Q, \delta, Q_0, \mathcal{F})$$

Q, δ, Q_0 as for standard Büchi automata

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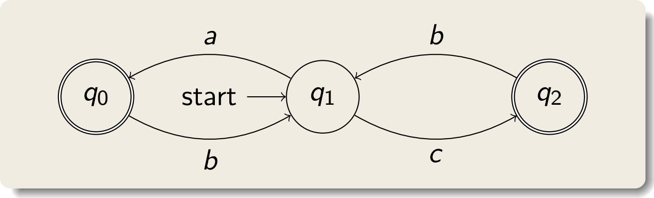
Definition (Acceptance for generalised Büchi automata)

A generalised Büchi automaton accepts an ω-word $w \in \Sigma^\omega$ iff
for every $i \in \{1, \ldots, k\}$ at least one $q \in F_i$ is visited infinitely often.

Generalised vs. Normal Büchi Automata: Example



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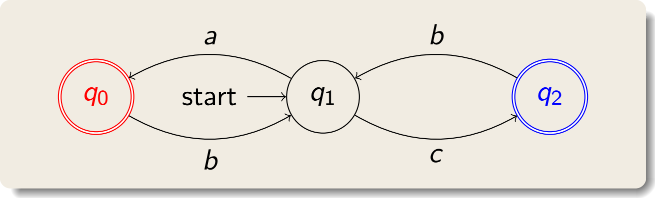

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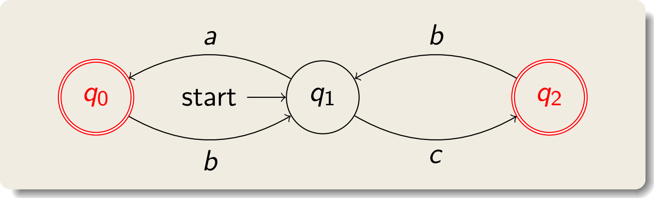

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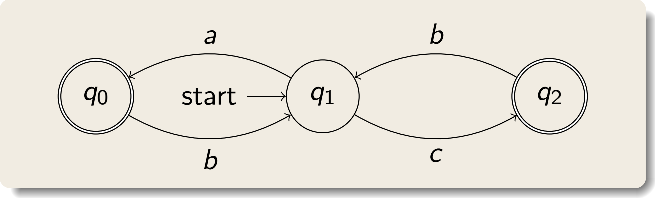

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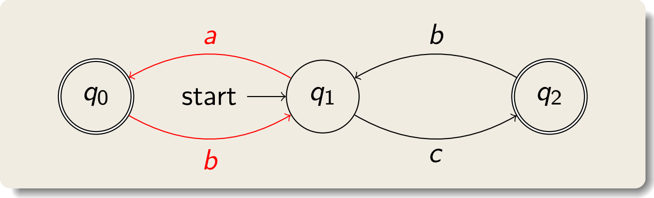

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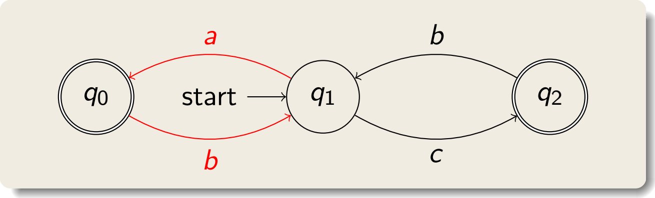

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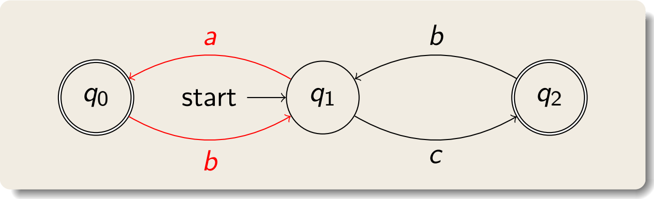

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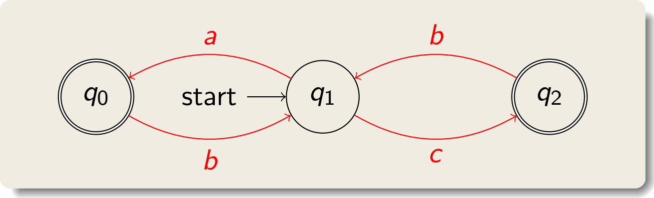

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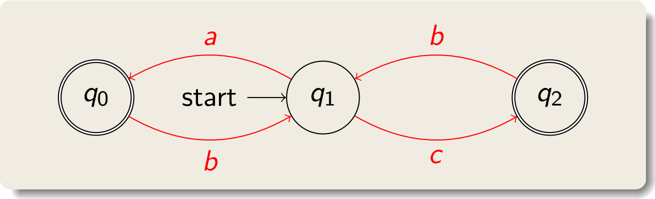

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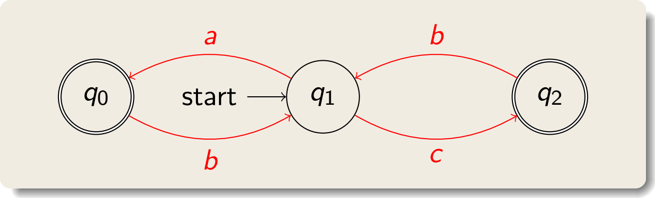

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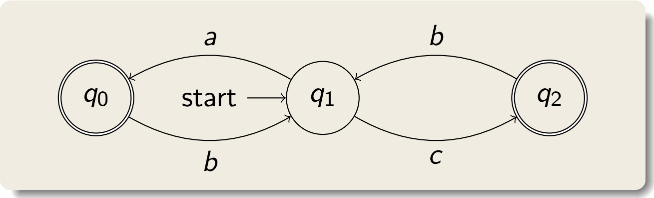

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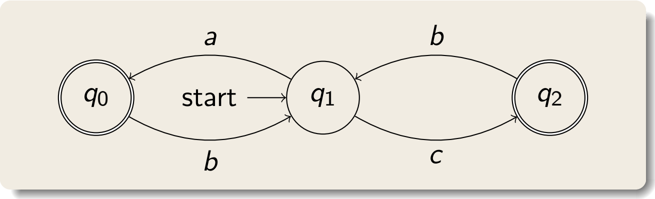

Construct $\mathcal{B}$ (different from last slide) which accepts the same words:

$$\mathcal{L}(\mathcal{B}) = \mathcal{L}(\mathcal{GB})$$

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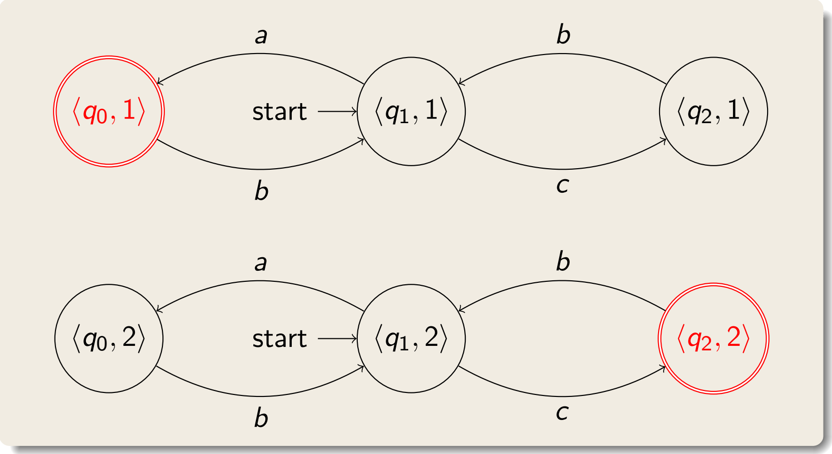
Construct $\mathcal{B}$ for $\mathcal{GB}$ with $\mathcal{F} = \{\overbrace{\{q_0\}}^{F_1}, \overbrace{\{q_2\}}^{F_2}\}$:



One clone for each $F_i \in \mathcal{F}$

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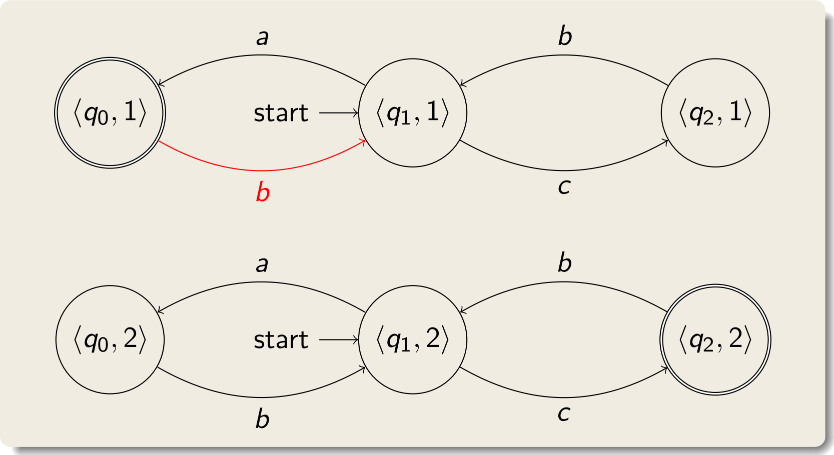

Every transition from "F_1" is redirected to "clone 2"

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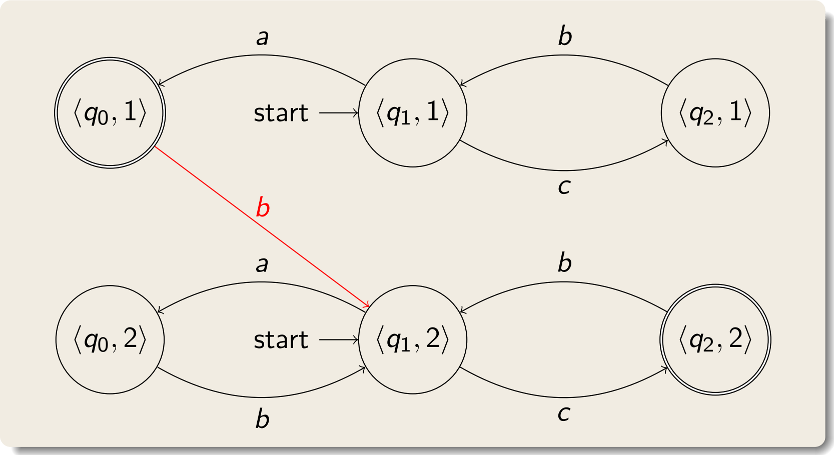

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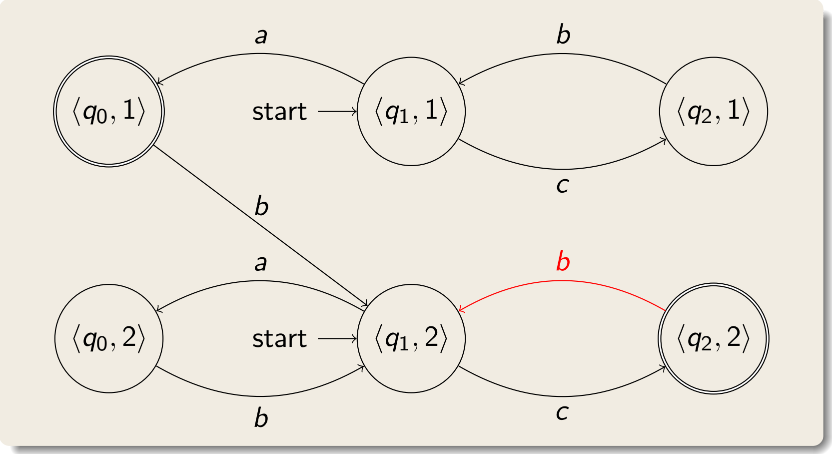

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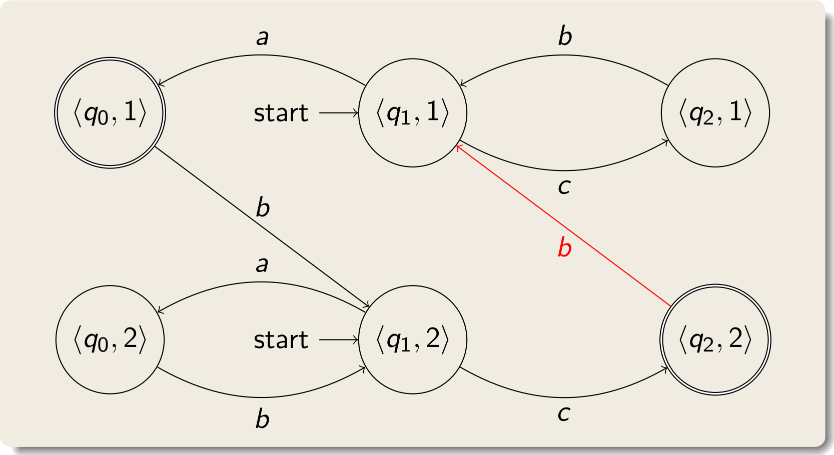

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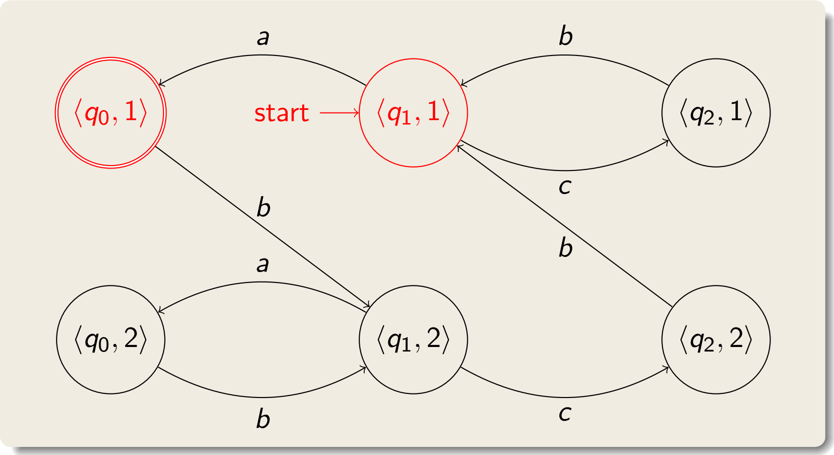

Keep only initial and accepting locations of "clone 1"

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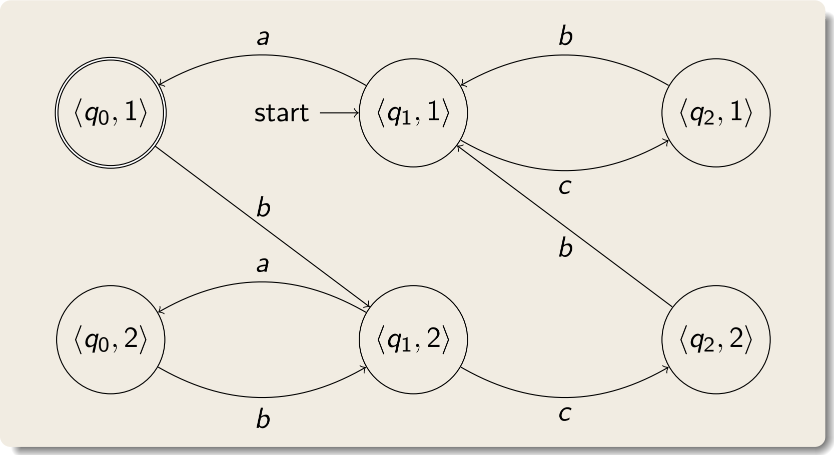

resulting *normal* Büchi automaton $\mathcal{B}$ with $\mathcal{L}(\mathcal{B}) = \mathcal{L}(\mathcal{GB})$

Translate Generalised to Normal Büchi Automata (formal)

Given generalised Büchi automaton
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Construction of a Generalised Büchi Automaton $\mathcal{GB}_\phi$ for an LTL-Formula ϕ

Focus on $\Box$-free and $\Diamond$-free LTL

- Following construction assumes formulas without $\Box$ and $\Diamond$.
- Only temporal modality is $\mathcal{U}$.
- $\Box$ can be removed using

$$\Box\phi \quad \equiv \quad \neg\Diamond\neg\phi$$

- $\Diamond$ can be removed using

$$\Diamond\phi \quad \equiv \quad \mathrm{true}\,\mathcal{U}\phi$$

Theory and Example at Once

We introduce the general consruction togher with example.

Task:

construct

$$\mathcal{GB}_\phi$$

for

$$\phi \equiv r\,\mathcal{U}s$$

Fischer-Ladner Closure

Fischer-Ladner closure of an LTL-formula ϕ

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$FL(r\,\mathcal{U}s) = \{r, \neg r, s, \neg s, r\,\mathcal{U}s, \neg(r\,\mathcal{U}s)\}$

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Until Consistent
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- $\neg(\psi_1 \mathcal{U} \psi_2) \in q$ then $\neg\psi_2 \in q$

$\mathcal{B}_\phi$-Construction: Locations

consistent, total	$\in Q$
$\{\neg(r\,\mathcal{U}s), \neg r, \neg s\}$	
$\{\neg(r\,\mathcal{U}s), \neg r, s\}$	
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$\{r\,\mathcal{U}s, \neg r, s\}$	
$\{r\,\mathcal{U}s, r, \neg s\}$	
$\{r\,\mathcal{U}s, r, s\}$	

$\mathcal{B}_\phi$-Construction: Locations

consistent, total	$\in Q$
$\{\neg(r\,\mathcal{U}s), \neg r, \neg s\}$	✔
$\{\neg(r\,\mathcal{U}s), \neg r, s\}$	
$\{\neg(r\,\mathcal{U}s), r, \neg s\}$	
$\{\neg(r\,\mathcal{U}s), r, s\}$	
$\{r\,\mathcal{U}s, \neg r, \neg s\}$	
$\{r\,\mathcal{U}s, \neg r, s\}$	
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$\{\neg(r\,\mathcal{U}s), \neg r, s\}$	✘
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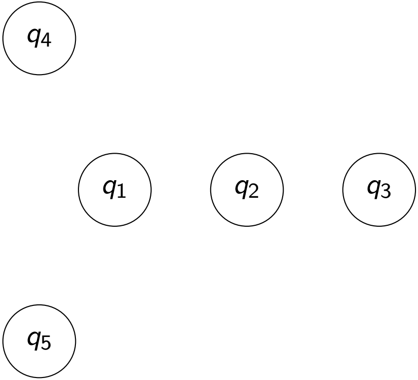
$\{r\,\mathcal{U}s, r, s\}$	✔

Locations of $\mathcal{B}_\phi$ are sets of formulas which can be simultaneously true

$\mathcal{B}_\phi$-Construction: Transitions

$$\underbrace{\{r\,\mathcal{U}s, \neg r, s\}}_{q_1}, \underbrace{\{r\,\mathcal{U}s, r, \neg s\}}_{q_2}, \underbrace{\{r\,\mathcal{U}s, r, s\}}_{q_3}, \underbrace{\{\neg(r\,\mathcal{U}s), r, \neg s\}}_{q_4}, \underbrace{\{\neg(r\,\mathcal{U}s), \neg r, \neg s\}}_{q_5}$$



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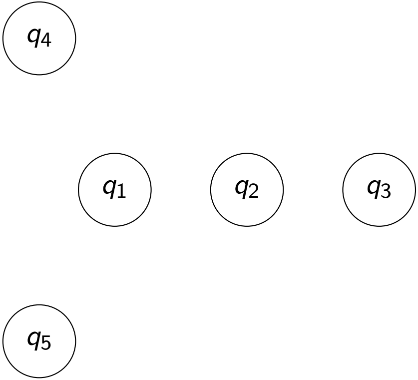

Transitions $(q, \alpha, q') \in \delta_\phi$:

such that

1. $\alpha = q \cap AP$
   (AP: atomic propositions)
2. If $\psi_1\,\mathcal{U}\psi_2 \in q$ and $\neg\psi_2 \in q$
   then $\psi_1\,\mathcal{U}\psi_2 \in q'$
3. If $\neg(\psi_1\,\mathcal{U}\psi_2) \in q$ and
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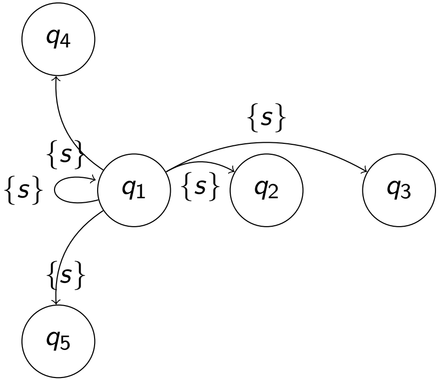

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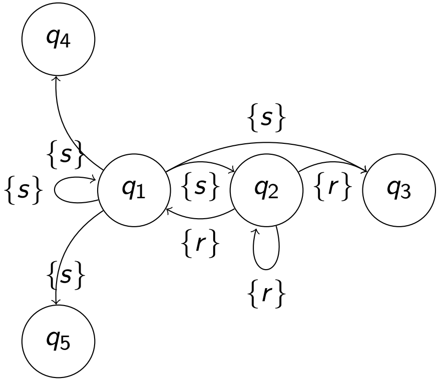

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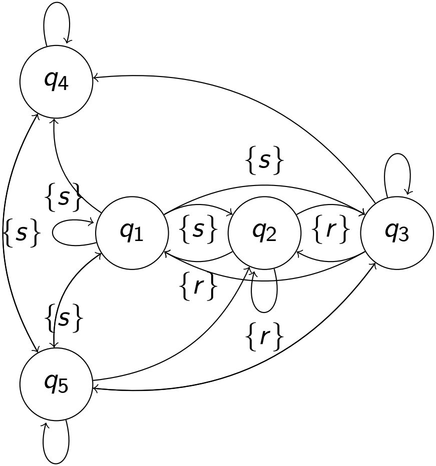

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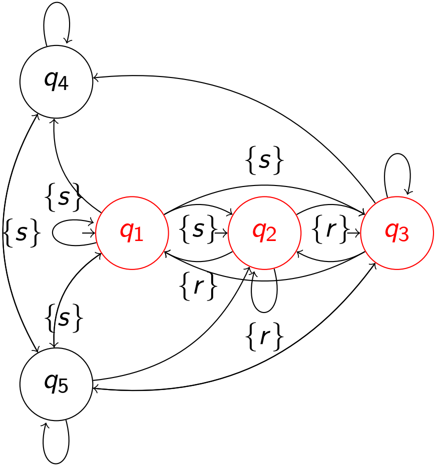

Initial locations

$q \in I_\phi$ iff $\phi \in q$

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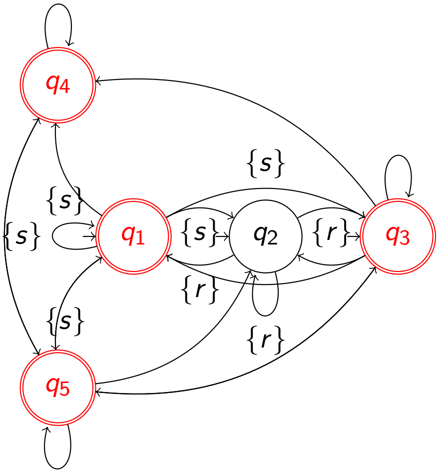

Initial locations

$$q \in I_\phi \text{ iff } \phi \in q$$

Accepting locations

$$\mathcal{F} = \{F_1, \ldots, F_n\}$$

- One F_i for each $\psi_{i1}\,\mathcal{U}\psi_{i2} \in FL(\phi)$;
  Example: $\mathcal{F} = \{F_1\}$
- F_i set of locations that do *not* contain $\psi_{i1}\,\mathcal{U}\psi_{i2}$ or that contain ψ_{i2}
  Ex.: $F_1 = \{q_1, q_3, q_4, q_5\}$

Remarks on Generalized Büchi Automata

- Construction always gives exponential number of states in $|\phi|$
- Satisfiability checking of LTL is PSPACE-complete
- There exist (more complex) constructions that minimize number of required states
  - One of these is used in SPIN, which moreover computes the states lazily

Part II

Starting First-order Logic

Motivation for Introducing First-Order Logic

1) We specify JAVA programs with Java Modeling Language (JML)

JML combines

- JAVA expressions
- First-Order Logic (FOL)

2) We verify JAVA programs using Dynamic Logic

Dynamic Logic combines

- First-Order Logic (FOL)
- JAVA programs

FOL: Language and Calculus

We introduce:

- FOL as a language
- Sequent calculus for proving FOL formulas
- KeY system as propositional, and first-order, prover (for now)
- Formal semantics

First-Order Logic: Signature

Signature

A first-order signature Σ consists of

- a set T_Σ of types
- a set F_Σ of function symbols
- a set P_Σ of predicate symbols
- a typing α_Σ

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Intuitively, the typing α_Σ determines

- for each function and predicate symbol:
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  - its argument types
- for each function symbol its result type.

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  - its argument types
- for each function symbol its result type.

Formally:

- $\alpha_\Sigma(p) \in {T_\Sigma}^*$ for all $p \in P_\Sigma$ (arity of p is $|\alpha_\Sigma(p)|$)
- $\alpha_\Sigma(f) \in {T_\Sigma}^* \times T_\Sigma$ for all $f \in F_\Sigma$ (arity of f is $|\alpha_\Sigma(f)| - 1$)

Example Signature Σ_1 + Constants

$T_{\Sigma_1} = \{\texttt{int}\}$,
$F_{\Sigma_1} = \{\texttt{+}, \texttt{-}\} \cup \{\ldots, \texttt{-2}, \texttt{-1}, \texttt{0}, \texttt{1}, \texttt{2}, \ldots\}$,
$P_{\Sigma_1} = \{\texttt{<}\}$

$\alpha_{\Sigma_1}(\texttt{<}) = (\texttt{int},\texttt{int})$
$\alpha_{\Sigma_1}(\texttt{+}) = \alpha_{\Sigma_1}(\texttt{-}) = (\texttt{int},\texttt{int},\texttt{int})$
$\alpha_{\Sigma_1}(\texttt{0}) = \alpha_{\Sigma_1}(\texttt{1}) = \alpha_{\Sigma_1}(\texttt{-1}) = \ldots = (\texttt{int})$

Constant Symbols

A function symbol `f` with $|\alpha_{\Sigma_1}(f)| = 1$ (i.e., with arity 0) is called *constant symbol*.

Here, the constant symbols are: $\ldots, \texttt{-2}, \texttt{-1}, \texttt{0}, \texttt{1}, \texttt{2}, \ldots$

Syntax of First-Order Logic: Signature Cont'd

Type declaration of signature symbols

- Write $\tau\ x$; to declare variable x of type τ
- Write $p(\tau_1, \ldots, \tau_r)$; for $\alpha(p) = (\tau_1, \ldots, \tau_r)$
- Write $\tau\ f(\tau_1, \ldots, \tau_r)$; for $\alpha(f) = (\tau_1, \ldots, \tau_r, \tau)$

$r = 0$ is allowed, then write f instead of $f()$.

Example

Variables	`integerArray a; int i;`
Predicate Symbols	`isEmpty(List); alertOn;`
Function Symbols	`int arrayLookup(int); Object o;`

Example Signature Σ_1 + Notation

Typing of Signature:

$\alpha_{\Sigma_1}(\texttt{<}) = (\texttt{int},\texttt{int})$
$\alpha_{\Sigma_1}(\texttt{+}) = \alpha_{\Sigma_1}(\texttt{-}) = (\texttt{int},\texttt{int},\texttt{int})$
$\alpha_{\Sigma_1}(\texttt{0}) = \alpha_{\Sigma_1}(\texttt{1}) = \alpha_{\Sigma_1}(\texttt{-1}) = \ldots = (\texttt{int})$

can alternatively be written as:

```
<(int,int);
int +(int,int);
int 0;  int 1;  int -1;  ...
```

First-Order Terms

We assume a set V of variables ($V \cap (F_\Sigma \cup P_\Sigma) = \emptyset$).
Each $v \in V$ has a unique type $\alpha_\Sigma(v) \in T_\Sigma$.

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Terms are defined recursively:

Terms

A first-order term of type $\tau \in T_\Sigma$

- is either a variable of type τ, or
- has the form $f(t_1, \ldots, t_n)$,
  where $f \in F_\Sigma$ has result type τ, and each t_i is term of the correct type, following the typing α_Σ of f.

If f is a constant symbol, the term is written f, instead of $f()$.

Terms over Signature Σ_1

Example terms over Σ_1:
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- `+(-2, 99)`
- `-(7, 8)`
- `+(-(7, 8), 1)`
- `+(-(`v_1`, 8), `v_2`)`

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Our variant of FOL allows infix notation for common functions:

- `-2 + 99`
- `7 - 8`
- `(7 - 8) + 1`
- `(`v_1` - 8) + `v_2

Atomic Formulas

Atomic Formulas

Given a signature Σ.
An atomic formula has either of the forms

- *true*
- *false*
- $t_1 = t_2$ *("equality")*,
  where t_1 and t_2 are first-order terms of the same type.
- $p(t_1, \ldots, t_n)$ *("predicate")*,
  where $p \in P_\Sigma$, and each t_i is term of the correct type, following the typing α_Σ of p.

Atomic Formulas over Signature Σ_1

Example formulas over Σ_1:
(assume variable `int` v;)

- $7 = 8$
- $<(7,\ 8)$
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Atomic Formulas over Signature Σ_1

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- `<(7, 8)`
- `<(-2 -` v`, 99)`
- `<(`v`,` v `+ 1)`

Our variant of FOL allows infix notation for common predicates:

- `7 < 8`
- `-2 -` v `< 99`
- v `<` v `+ 1`

First-Order Formulas

Formulas

- each atomic formula is a formula
- with ϕ and ψ formulas, x a variable, and τ a type, the following are also formulas:
  - $\neg\phi$ *("not ϕ")*
  - $\phi \wedge \psi$ *("ϕ and ψ")*
  - $\phi \vee \psi$ *("ϕ or ψ")*
  - $\phi \rightarrow \psi$ *("ϕ implies ψ")*
  - $\phi \leftrightarrow \psi$ *("ϕ is equivalent to ψ")*

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  - $\phi \lor \psi$ *("ϕ or ψ")*
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  - $\phi \leftrightarrow \psi$ *("ϕ is equivalent to ψ")*
  - $\forall\ \tau\ x;\ \phi$ *("for all x of type τ holds ϕ")*
  - $\exists\ \tau\ x;\ \phi$ *("there exists an x of type τ such that ϕ")*

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Formulas with no free variable are 'closed'.

First-order Formulas: Examples

(signatures/types left out here)

Example (There are at least two elements)

First-order Formulas: Examples

(signatures/types left out here)

Example (There are at least two elements)

$\exists x, y; \neg(x = y)$

First-order Formulas: Examples

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Example (Strict partial order)

First-order Formulas: Examples

(signatures/types left out here)

Example (Strict partial order)

Irreflexivity	$\forall x; \neg(x < x)$
Asymmetry	$\forall x; \forall y; (x < y \rightarrow \neg(y < x))$
Transitivity	$\forall x; \forall y; \forall z;$ $(x < y \land y < z \rightarrow x < z)$

First-order Formulas: Examples

(signatures/types left out here)

Example (Strict partial order)

Irreflexivity	$\forall x; \neg(x < x)$
Asymmetry	$\forall x; \forall y; (x < y \to \neg(y < x))$
Transitivity	$\forall x; \forall y; \forall z;$ $(x < y \land y < z \to x < z)$

(Is any of the three formulas redundant?)

Semantics (briefly here, more thorough later)

Domain

A domain $\mathcal{D}$ is a set of elements which are (potentially) the *meaning* of terms and variables.

Interpretation

An interpretation $\mathcal{I}$ (over $\mathcal{D}$) assigns *meaning* to the symbols in $F_\Sigma \cup P_\Sigma$ (assigning functions to function symbols, relations to predicate symbols).

Valuation

In a given $\mathcal{D}$ and $\mathcal{I}$, a closed formula evaluates to either T or F.

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A closed formula is valid if it evaluates to T in all $\mathcal{D}$ and $\mathcal{I}$.

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A closed formula is valid if it evaluates to T in all $\mathcal{D}$ and $\mathcal{I}$.

In the context of specification/verification of programs:
each $(\mathcal{D}, \mathcal{I})$ is called a 'state'.

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Let ϕ and ψ be arbitrary, closed formulas (whether valid or not).

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- $\neg(\phi \vee \psi) \leftrightarrow$

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Let ϕ and ψ be arbitrary, closed formulas (whether valid or not).

The following formulas are valid:

- $\neg(\phi \wedge \psi) \leftrightarrow \neg\phi \vee \neg\psi$
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- $(\phi \to \psi) \leftrightarrow (\neg\phi \lor \psi)$
- $\phi \to \mathit{true}$

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Are the following formulas also valid?

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Remark on Concrete Syntax

	Text book	Spin	KeY
Negation	$\neg$	`!`	`!`
Conjunction	$\wedge$	`&&`	`&`
Disjunction	$\vee$	`||`	`|`
Implication	$\rightarrow, \supset$	`->`	`->`
Equivalence	$\leftrightarrow$	`<->`	`<->`
Universal Quantifier	$\forall\, x; \phi$	n/a	`\forall` $\tau\ x; \phi$
Existential Quantifier	$\exists\, x; \phi$	n/a	`\exists` $\tau\ x; \phi$
Value equality	$=$	`==`	`=`

Motivation for a Sequent Calculus

How to show a formula valid in propositional logic?
$\rightarrow$ use a semantic truth table.

How about FOL? Formula: $\texttt{isEven}(x) \vee \texttt{isOdd}(x)$

x	$\texttt{isEven}(x)$	$\texttt{isOdd}(x)$	$\texttt{isEven}(x) \vee \texttt{isOdd}(x)$
1	F	T	T
2	T	F	T
...	...	...	...

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Checking validity via **semantics** does not work.

Instead...

Reasoning by Syntactic Transformation

Prove validity of ϕ by **syntactic** transformation of ϕ

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Logic Calculus: Sequent Calculus based on notion of sequent:

$$\underbrace{\psi_1, \ldots, \psi_m}_{\text{antecedent}} \quad \Longrightarrow \quad \underbrace{\phi_1, \ldots, \phi_n}_{\text{succedent}}$$

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has same meaning as

$$(\psi_1 \wedge \cdots \wedge \psi_m) \quad \rightarrow \quad (\phi_1 \vee \cdots \vee \phi_n)$$

which has (for closed formulas ψ_i, ϕ_i) same meaning as

$$\{\psi_1, \ldots, \psi_m\} \quad \models \quad \phi_1 \vee \cdots \vee \phi_n$$

Notation for Sequents

$$\psi_1, \ldots, \psi_m \quad \Longrightarrow \quad \phi_1, \ldots, \phi_n$$

Consider antecedent/succedent as sets of formulas, may be empty

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Schema Variables

$\phi, \psi, \ldots$ match formulas, $\Gamma, \Delta, \ldots$ match sets of formulas
Characterize infinitely many sequents with single schematic sequent, e.g.,

$$\Gamma \quad \Longrightarrow \quad \phi \wedge \psi, \Delta$$

matches any sequent with occurrence of conjunction in succedent

Here, we call $\phi \wedge \psi$ main formula and Γ, Δ side formulas of sequent

Sequent Calculus Rules

Write syntactic transformation schema for sequents that reflects semantics of connectives

$$\text{RuleName}\ \frac{\overbrace{\Gamma_1 \Longrightarrow \Delta_1 \quad \cdots \quad \Gamma_r \Longrightarrow \Delta_r}^{\text{premisses}}}{\underbrace{\Gamma \Longrightarrow \Delta}_{\text{conclusion}}}$$

Meaning: For proving the conclusion, it suffices to prove all premisses.

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Example

$$\text{andRight}\ \frac{\Gamma \Longrightarrow \phi, \Delta \qquad \Gamma \Longrightarrow \psi, \Delta}{\Gamma \Longrightarrow \phi \land \psi, \Delta}$$

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$$\text{andRight}\ \frac{\Gamma \Longrightarrow \phi, \Delta \qquad \Gamma \Longrightarrow \psi, \Delta}{\Gamma \Longrightarrow \phi \wedge \psi, \Delta}$$

Admissible to have no premisses (iff conclusion is valid, e.g., axiom)

A rule is sound (correct) iff the validity of its premisses implies the validity of its conclusion.

'Propositional' Sequent Calculus Rules

$$\text{close} \quad \frac{}{\Gamma, \phi \Longrightarrow \phi, \Delta}$$

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close $\dfrac{}{\Gamma, \phi \Longrightarrow \phi, \Delta}$ true $\dfrac{}{\Gamma \Longrightarrow \mathrm{true}, \Delta}$

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	left side (antecedent)	right side (succedent)
not	$\dfrac{\Gamma \Longrightarrow \phi, \Delta}{\Gamma, \neg\phi \Longrightarrow \Delta}$	$\dfrac{\Gamma, \phi \Longrightarrow \Delta}{\Gamma \Longrightarrow \neg\phi, \Delta}$

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imp	$\dfrac{\Gamma \Longrightarrow \phi, \Delta \qquad \Gamma, \psi \Longrightarrow \Delta}{\Gamma, \phi \to \psi \Longrightarrow \Delta}$	$\dfrac{\Gamma, \phi \Longrightarrow \psi, \Delta}{\Gamma \Longrightarrow \phi \to \psi, \Delta}$

Sequent Calculus Proofs

Goal to prove: $\mathcal{G} = \quad \psi_1, \ldots, \psi_m \implies \phi_1, \ldots, \phi_n$

- find rule $\mathcal{R}$ whose conclusion matches $\mathcal{G}$
- instantiate $\mathcal{R}$ such that its conclusion is identical to $\mathcal{G}$
- apply that instantiation to all premisses of $\mathcal{R}$, resulting in new goals $\mathcal{G}_1$, ..., $\mathcal{G}_r$
- recursively find proofs for $\mathcal{G}_1$, ..., $\mathcal{G}_r$
- tree structure with goal as root
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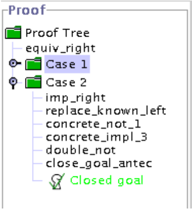
Goal-directed proof search

- Paper proofs: root at bottom, grow upwards
- KeY tool proofs: root at top, grow downwards



A Simple Proof

$$\dfrac{\dfrac{\dfrac{\dfrac{\overline{} \quad \overline{}}{}}{}}{}}{\Longrightarrow (p \land (p \to q)) \to q}$$

A Simple Proof

$$\dfrac{\dfrac{\dfrac{\dfrac{\overline{} \qquad \overline{}}{}}{}}{p \wedge (p \rightarrow q) \Longrightarrow q}}{\Longrightarrow (p \wedge (p \rightarrow q)) \rightarrow q}$$

A Simple Proof

$$\cfrac{\cfrac{\cfrac{\overline{\qquad} \qquad \overline{\qquad}}{p,\, (p \to q) \Longrightarrow q}}{p \wedge (p \to q) \Longrightarrow q}}{\Longrightarrow (p \wedge (p \to q)) \to q}$$

A Simple Proof

$$
\dfrac{\dfrac{\dfrac{\dfrac{}{p \Longrightarrow p,\ q} \qquad \dfrac{}{p,\ q \Longrightarrow q}}{p,\ (p \rightarrow q) \Longrightarrow q}}{p \wedge (p \rightarrow q) \Longrightarrow q}}{\Longrightarrow (p \wedge (p \rightarrow q)) \rightarrow q}
$$

A Simple Proof

$$
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$$

A Simple Proof

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$$

A proof is closed iff all its branches are closed

Demo

`prop.key`

Proving Validity of First-Order Formulas

Proving a universally quantified formula

Claim: $\forall \tau\, x;\ \phi$ is true

How is such a claim proved in mathematics?

All even numbers are divisible by 2	$\forall\, \mathbf{int}\, x;\ (\mathsf{even}(x) \rightarrow \mathsf{divByTwo}(x))$
Let c be an arbitrary number	Declare "unused" constant $\mathbf{int}$ c
The even number c is divisible by 2	prove $\mathsf{even}(c) \rightarrow \mathsf{divByTwo}(c)$

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Sequent rule $\forall$-right

$$\text{forallRight}\ \frac{\Gamma \Longrightarrow [x/c]\,\phi, \Delta}{\Gamma \Longrightarrow \forall \tau\, x;\ \phi, \Delta}$$

- $[x/c]\,\phi$ is result of replacing each occurrence of x in ϕ with c
- c **new** constant of type τ

Proving Validity of First-Order Formulas Cont'd

Proving an existentially quantified formula

Claim: $\exists\, \tau\, x;\ \phi$ is true

How is such a claim proved in mathematics?

There is at least one prime number	$\exists\, \mathbf{int}\, x;$ prime(x)
Provide any "witness", say, 7	Use variable-free term $\mathbf{int}\ 7$
7 is a prime number	prime(7)

Proving Validity of First-Order Formulas Cont'd

Proving an existentially quantified formula

Claim: $\exists\,\tau\,x;\ \phi$ is true

How is such a claim proved in mathematics?

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Provide any "witness", say, 7	Use variable-free term $\mathbf{int}\ 7$
7 is a prime number	$\mathrm{prime}(7)$

Sequent rule $\exists$-right

$$\text{existsRight}\ \frac{\Gamma \Longrightarrow [x/t]\,\phi,\ \exists\,\tau\,x;\ \phi, \Delta}{\Gamma \Longrightarrow \exists\,\tau\,x;\ \phi, \Delta}$$

- t any variable-free term of type τ
- We might need other instances besides t! Keep $\exists\,\tau\,x;\ \phi$

Proving Validity of First-Order Formulas Cont'd

Using a universally quantified formula

We assume $\forall \tau\, x;\ \phi$ is true

How is such a fact used in a mathematical proof?

We know that all primes are odd	$\forall\, \mathbf{int}\, x;\ (\mathrm{prime}(x) \rightarrow \mathrm{odd}(x))$
In particular, this holds for 17	Use variable-free term $\mathbf{int}$ 17
We know: if 17 is prime it is odd	$\mathrm{prime}(17) \rightarrow \mathrm{odd}(17)$

Proving Validity of First-Order Formulas Cont'd

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We know: if 17 is prime it is odd	$\mathsf{prime}(17) \rightarrow \mathsf{odd}(17)$

Sequent rule $\forall$-left

$$\mathsf{forallLeft}\ \frac{\Gamma, \forall \tau\, x;\ \phi,\ [x/t]\,\phi \Longrightarrow \Delta}{\Gamma, \forall \tau\, x;\ \phi \Longrightarrow \Delta}$$

- t any variable-free term of type τ
- We might need other instances besides t! Keep $\forall \tau\, x;\ \phi$

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

We assume $\exists \tau\, x; \phi$ is true

How is such a fact used in a mathematical proof?

We know such an element exists. Let's give it a new name for future reference.

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

We assume $\exists \tau\, x;\ \phi$ is true

How is such a fact used in a mathematical proof?

We know such an element exists. Let's give it a new name for future reference.

Sequent rule $\exists$-left

$$\text{existsLeft}\ \frac{\Gamma, [x/c]\,\phi \Longrightarrow \Delta}{\Gamma, \exists \tau\, x;\ \phi \Longrightarrow \Delta}$$

- c **new** constant of type τ

Proving Validity of First-Order Formulas Cont'd

Using an equation between terms

We assume $t = t'$ is true

How is such a fact used in a mathematical proof?

$x = y{-}1 \Longrightarrow 1 = x{+}1/y$

Use $x = y{-}1$ to modify $x{+}1/y$:
replace x in succedent with right-hand side of antecedent

Proving Validity of First-Order Formulas Cont'd

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Proving Validity of First-Order Formulas Cont'd

Using an equation between terms

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replace x in succedent with right-hand side of antecedent

$x = y-1 \Longrightarrow 1 = y-1+1/y$

Sequent rule $=$-left

$$\text{applyEqL}\ \frac{\Gamma, t = t', [t/t']\,\phi \Longrightarrow \Delta}{\Gamma, t = t', \phi \Longrightarrow \Delta} \qquad \text{applyEqR}\ \frac{\Gamma, t = t' \Longrightarrow [t/t']\,\phi, \Delta}{\Gamma, t = t' \Longrightarrow \phi, \Delta}$$

- Always replace left- with right-hand side (use eqSymm if necessary)
- t, t' variable-free terms of the same type

Proving Validity of First-Order Formulas Cont'd

Closing a subgoal in a proof

- We derived a sequent that is obviously valid

$$\text{close}\ \frac{}{\Gamma, \phi \Longrightarrow \phi, \Delta} \qquad \text{true}\ \frac{}{\Gamma \Longrightarrow \mathrm{true}, \Delta} \qquad \text{false}\ \frac{}{\Gamma, \mathrm{false} \Longrightarrow \Delta}$$

- We derived an equation that is obviously valid

$$\text{eqClose}\ \frac{}{\Gamma \Longrightarrow t = t, \Delta}$$

Sequent Calculus for FOL at One Glance

	left side, antecedent	right side, succedent
$\forall$	$\dfrac{\Gamma, \forall \tau\, x;\ \phi,\ [x/t']\,\phi \Longrightarrow \Delta}{\Gamma, \forall \tau\, x;\ \phi \Longrightarrow \Delta}$	$\dfrac{\Gamma \Longrightarrow [x/c]\,\phi, \Delta}{\Gamma \Longrightarrow \forall \tau\, x;\ \phi, \Delta}$
$\exists$	$\dfrac{\Gamma, [x/c]\,\phi \Longrightarrow \Delta}{\Gamma, \exists \tau\, x;\ \phi \Longrightarrow \Delta}$	$\dfrac{\Gamma \Longrightarrow [x/t']\,\phi,\ \exists \tau\, x;\ \phi, \Delta}{\Gamma \Longrightarrow \exists \tau\, x;\ \phi, \Delta}$
$=$	$\dfrac{\Gamma, t = t' \Longrightarrow [t/t']\,\phi, \Delta}{\Gamma, t = t' \Longrightarrow \phi, \Delta}$ (+ application rule on left side)	$\dfrac{}{\Gamma \Longrightarrow t = t, \Delta}$

- $[t/t']\,\phi$ is result of replacing each occurrence of t in ϕ with t'
- t,t' variable-free terms of type τ
- c **new** constant of type τ (occurs not on current proof branch)
- Equations can be reversed by commutativity

Recap: ‘Propositional’ Sequent Calculus Rules

main	left side (antecedent)	right side (succedent)
not	$\dfrac{\Gamma \Longrightarrow \phi, \Delta}{\Gamma, \neg\phi \Longrightarrow \Delta}$	$\dfrac{\Gamma, \phi \Longrightarrow \Delta}{\Gamma \Longrightarrow \neg\phi, \Delta}$
and	$\dfrac{\Gamma, \phi, \psi \Longrightarrow \Delta}{\Gamma, \phi \wedge \psi \Longrightarrow \Delta}$	$\dfrac{\Gamma \Longrightarrow \phi, \Delta \qquad \Gamma \Longrightarrow \psi, \Delta}{\Gamma \Longrightarrow \phi \wedge \psi, \Delta}$
or	$\dfrac{\Gamma, \phi \Longrightarrow \Delta \qquad \Gamma, \psi \Longrightarrow \Delta}{\Gamma, \phi \vee \psi \Longrightarrow \Delta}$	$\dfrac{\Gamma \Longrightarrow \phi, \psi, \Delta}{\Gamma \Longrightarrow \phi \vee \psi, \Delta}$
imp	$\dfrac{\Gamma \Longrightarrow \phi, \Delta \qquad \Gamma, \psi \Longrightarrow \Delta}{\Gamma, \phi \rightarrow \psi \Longrightarrow \Delta}$	$\dfrac{\Gamma, \phi \Longrightarrow \psi, \Delta}{\Gamma \Longrightarrow \phi \rightarrow \psi, \Delta}$

close $\dfrac{}{\Gamma, \phi \Longrightarrow \phi, \Delta}$ true $\dfrac{}{\Gamma \Longrightarrow \mathrm{true}, \Delta}$ false $\dfrac{}{\Gamma, \mathrm{false} \Longrightarrow \Delta}$

Proving Validity of First-Order Formulas Cont'd

Example (A simple theorem about binary relations)

$$\exists\, x;\, \forall\, y;\, p(x,y) \Longrightarrow \forall\, y;\, \exists\, x;\, p(x,y)$$

Untyped logic: let static type of x and y be $\top$

Proving Validity of First-Order Formulas Cont'd

Example (A simple theorem about binary relations)

$$\frac{\forall\, y;\ p(c, y) \Longrightarrow \forall\, y;\ \exists\, x;\ p(x, y)}{\exists\, x;\ \forall\, y;\ p(x, y) \Longrightarrow \forall\, y;\ \exists\, x;\ p(x, y)}$$

$\exists$-left: substitute new constant c of type $\top$ for x

Proving Validity of First-Order Formulas Cont'd

Example (A simple theorem about binary relations)

$$\cfrac{\cfrac{\forall\, y;\ p(c, y) \Longrightarrow \exists\, x;\ p(x, d)}{\forall\, y;\ p(c, y) \Longrightarrow \forall\, y;\ \exists\, x;\ p(x, y)}}{\exists\, x;\ \forall\, y;\ p(x, y) \Longrightarrow \forall\, y;\ \exists\, x;\ p(x, y)}$$

$\forall$-right: substitute new constant d of type $\top$ for y

Proving Validity of First-Order Formulas Cont'd

Example (A simple theorem about binary relations)

$$\cfrac{\cfrac{\cfrac{p(c, d), \forall y;\ p(c, y) \Longrightarrow \exists x;\ p(x, d)}{\forall y;\ p(c, y) \Longrightarrow \exists x;\ p(x, d)}}{\forall y;\ p(c, y) \Longrightarrow \forall y;\ \exists x;\ p(x, y)}}{\exists x;\ \forall y;\ p(x, y) \Longrightarrow \forall y;\ \exists x;\ p(x, y)}$$

$\forall$-left: free to substitute any term of type $\top$ for y, choose d

Proving Validity of First-Order Formulas Cont'd

Example (A simple theorem about binary relations)

$$\dfrac{\dfrac{\dfrac{\dfrac{p(c,d),\ \forall y;\ p(c,y) \Longrightarrow p(c,d),\ \exists x;\ p(x,d)}{p(c,d),\ \forall y;\ p(c,y) \Longrightarrow \exists x;\ p(x,d)}}{\forall y;\ p(c,y) \Longrightarrow \exists x;\ p(x,d)}}{\forall y;\ p(c,y) \Longrightarrow \forall y;\ \exists x;\ p(x,y)}}{\exists x;\ \forall y;\ p(x,y) \Longrightarrow \forall y;\ \exists x;\ p(x,y)}$$

$\exists$-right: free to substitute any term of type $\top$ for x, choose c

Proving Validity of First-Order Formulas Cont'd

Example (A simple theorem about binary relations)

$$\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{*}{p(c,d),\ \forall\, y;\ p(c,y) \Longrightarrow p(c,d),\ \exists\, x;\ p(x,d)}}{p(c,d),\ \forall\, y;\ p(c,y) \Longrightarrow \exists\, x;\ p(x,d)}}{\forall\, y;\ p(c,y) \Longrightarrow \exists\, x;\ p(x,d)}}{\forall\, y;\ p(c,y) \Longrightarrow \forall\, y;\ \exists\, x;\ p(x,y)}}{\exists\, x;\ \forall\, y;\ p(x,y) \Longrightarrow \forall\, y;\ \exists\, x;\ p(x,y)}$$

Close

Proving Validity of First-Order Formulas Cont'd

Example (A simple theorem about binary relations)

$$\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{*}{p(c,d),\ \forall y;\ p(c,y) \Longrightarrow p(c,d),\ \exists x;\ p(x,d)}}{p(c,d),\ \forall y;\ p(c,y) \Longrightarrow \exists x;\ p(x,d)}}{\forall y;\ p(c,y) \Longrightarrow \exists x;\ p(x,d)}}{\forall y;\ p(c,y) \Longrightarrow \forall y;\ \exists x;\ p(x,y)}}{\exists x;\ \forall y;\ p(x,y) \Longrightarrow \forall y;\ \exists x;\ p(x,y)}$$

Demo

`relSimple.key`

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

Let x, y denote integer constants, both are not zero.

$\neg(x = 0), \neg(y = 0) \qquad \Longrightarrow$

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

Let x, y denote integer constants, both are not zero. We know further that x divides y.

$$\neg(x = 0), \neg(y = 0), \exists\, \texttt{int}\ k;\ y = k * x \Longrightarrow$$

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

Let x, y denote integer constants, both are not zero. We know further that x divides y.

Show: $(y/x) * x = y$ ('/' is division on integers, i.e., the equation is not always true, e.g. $x = 2, y = 1$)

$$\neg(x = 0), \neg(y = 0), \exists\, \texttt{int}\ k;\ y = k * x \Longrightarrow (y/x) * x = y$$

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

Let x, y denote integer constants, both are not zero. We know further that x divides y.
Show: $(y/x) * x = y$ ($'/'$ is division on integers, i.e., the equation is not always true, e.g. $x = 2, y = 1$)
Proof: We know x divides y, i.e. there exists a k such that $y = k * x$.
Let now c denote such a k.

$$\frac{\neg(x = 0), \neg(y = 0), y = c * x \Longrightarrow (y/x) * x = y}{\neg(x = 0), \neg(y = 0), \exists\, \texttt{int}\ k;\ y = k * x \Longrightarrow (y/x) * x = y}$$

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

Let x, y denote integer constants, both are not zero. We know further that x divides y.
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Proof: We know x divides y, i.e. there exists a k such that $y = k * x$. Let now c denote such a k. Hence we can replace y by $c * x$ on the right side.

$$\cfrac{\cfrac{\neg(x = 0), \neg(y = 0), y = c * x \Longrightarrow ((c * x)/x) * x = y}{\neg(x = 0), \neg(y = 0), y = c * x \Longrightarrow (y/x) * x = y}}{\neg(x = 0), \neg(y = 0), \exists\, \mathtt{int}\ k;\ y = k * x \Longrightarrow (y/x) * x = y}$$

Proving Validity of First-Order Formulas Cont'd

Using an existentially quantified formula

Let x, y denote integer constants, both are not zero. We know further that x divides y.
Show: $(y/x) * x = y$ ($'/'$ is division on integers, i.e., the equation is not always true, e.g. $x = 2, y = 1$)
Proof: We know x divides y, i.e. there exists a k such that $y = k * x$. Let now c denote such a k. Hence we can replace y by $c * x$ on the right side. . . . $\square$

$$\dfrac{\dfrac{\dfrac{\dfrac{*}{\vdots}}{\neg(x = 0), \neg(y = 0), y = c * x \Longrightarrow ((c * x)/x) * x = y}}{\neg(x = 0), \neg(y = 0), y = c * x \Longrightarrow (y/x) * x = y}}{\neg(x = 0), \neg(y = 0), \exists\, \mathtt{int}\ k;\ y = k * x \Longrightarrow (y/x) * x = y}$$

Features of the KeY Theorem Prover

Demo

`rel.key`, `twoInstances.key`

Feature List

- Can work on multiple proofs simultaneously (task list)
- Point-and-click navigation within proof
- Undo proof steps, prune proof trees
- Pop-up menu with proof rules applicable in pointer focus
- Preview of rule effect as tool tip
- Quantifier instantiation and equality rules by drag-and-drop
- Possible to hide (and unhide) parts of a sequent
- Saving and loading of proofs

Literature for this Lecture

KeYbook *W. Ahrendt*, B. Beckert, R. Bubel, R. Hähnle, P. Schmitt, M. Ulbrich, editors.
Deductive Software Verification - The KeY Book
Vol 10001 of *LNCS*, Springer, 2016
(E-book at `link.springer.com`)

- *W. Ahrendt*, S. Grebing, Using the KeY Prover
  Chapter 15 in [KeYbook]

further reading:

- P.H. Schmitt, First-Order Logic,
  Chapter 2 in [KeYbook]

Part III

First-Order Semantics

First-Order Semantics

From propositional to first-order semantics

- In prop. logic, an interpretation of variables with $\{T, F\}$ sufficed
- In first-order logic we must assign meaning to:
  - function symbols
  - predicate symbols
  - variables bound in quantifiers
- Respect typing: `int i`, `List l` must denote different items

First-Order Semantics

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- In prop. logic, an interpretation of variables with $\{T, F\}$ sufficed
- In first-order logic we must assign meaning to:
  - function symbols
  - predicate symbols
  - variables bound in quantifiers
- Respect typing: `int i`, `List l` must denote different items

What we need (to interpret a first-order formula)

1. A typed domain of items
2. A mapping from function symbols to functions on items
3. A mapping from predicate symbols to relation on items
4. A mapping from variables to items

First-Order Domains

1. A typed domain of items:

Definition (Typed Domain)

A non-empty set $\mathcal{D}$ of items is a domain.

A typing of $\mathcal{D}$ wrt. signature Σ is a mapping $\delta : \mathcal{D} \rightarrow T_\Sigma$

First-Order Domains

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We require from $\mathcal{D}$ and δ that no type is empty:
for each $\tau \in T_\Sigma$, there is a $d \in \mathcal{D}$ with $\delta(d) = \tau$

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We require from $\mathcal{D}$ and δ that no type is empty:
for each $\tau \in T_\Sigma$, there is a $d \in \mathcal{D}$ with $\delta(d) = \tau$

- If $\delta(d) = \tau$, we say d has type τ.
- $\mathcal{D}^\tau = \{d \in \mathcal{D} \mid \delta(d) = \tau\}$ is called subdomain of type τ.
- It follows that $\mathcal{D}^\tau \neq \emptyset$ for each $\tau \in T_\Sigma$.

First-Order States

2. A mapping from function symbol to functions on items
3. A mapping from predicate symbol to relation on items

Definition (Interpretation, First-Order State)

Let $\mathcal{D}$ be a domain with typing δ.

First-Order States

2. A mapping from function symbol to functions on items
3. A mapping from predicate symbol to relation on items

Definition (Interpretation, First-Order State)

Let $\mathcal{D}$ be a domain with typing δ.

Let $\mathcal{I}$ be a mapping, called interpretation, from function and predicate symbols to functions and relations on items, respectively, such that

First-Order States

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3. A mapping from predicate symbol to relation on items

Definition (Interpretation, First-Order State)

Let $\mathcal{D}$ be a domain with typing δ.

Let $\mathcal{I}$ be a mapping, called interpretation, from function and predicate symbols to functions and relations on items, respectively, such that

$$\begin{array}{ll} \mathcal{I}(f) : \mathcal{D}^{\tau_1} \times \cdots \times \mathcal{D}^{\tau_r} \to \mathcal{D}^{\tau} & \text{when } \alpha_\Sigma(f) = (\tau_1, \ldots, \tau_r, \tau) \\ \mathcal{I}(p) \subseteq \mathcal{D}^{\tau_1} \times \cdots \times \mathcal{D}^{\tau_r} & \text{when } \alpha_\Sigma(p) = (\tau_1, \ldots, \tau_r) \end{array}$$

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Then $\mathcal{S} = (\mathcal{D}, \delta, \mathcal{I})$ is a first-order state.

First-Order States Cont'd

Example

Signature: $\mathbf{int}$ `i;` $\mathbf{short}$ `j;` $\mathbf{int}$ `f(`$\mathbf{int}$`);` `Object obj;` `<(`$\mathbf{int}$`,`$\mathbf{int}$`);`

$\mathcal{D} = \{17, 2, o\}$ where all numbers are short

$$\mathcal{I}(i) = 17$$
$$\mathcal{I}(j) = 17$$
$$\mathcal{I}(\texttt{obj}) = o$$

$\mathcal{D}^{\mathbf{int}}$	$\mathcal{I}(f)$
2	2
17	2

$\mathcal{D}^{\mathbf{int}} \times \mathcal{D}^{\mathbf{int}}$	in $\mathcal{I}(<)$?
$(2, 2)$	F
$(2, 17)$	T
$(17, 2)$	F
$(17, 17)$	F

One of uncountably many possible first-order states!

Semantics of Equality

Definition

Interpretation is fixed as $\mathcal{I}(=) = \{(d, d) \mid d \in \mathcal{D}\}$

Exercise: write down the predicate table for example domain

Signature Symbols vs. Domain Elements

- Domain elements different from the terms representing them
- First-order formulas and terms have no access to domain

Example

Signature: `Object obj1, obj2;`
Domain: $\mathcal{D} = \{o\}$

In this state, necessarily $\mathcal{I}(\texttt{obj1}) = \mathcal{I}(\texttt{obj2}) = o$

Variable Assignments

4. A mapping from variables to items

Think of variable assignment as environment for storage of local variables

Definition (Variable Assignment)

A variable assignment β maps variables to domain elements.
It respects the variable type, i.e., if x has type τ then $\beta(x) \in \mathcal{D}^\tau$

Definition (Modified Variable Assignment)

Let y be variable of type τ, β variable assignment, $d \in \mathcal{D}^\tau$:

$$\beta_y^d(x) := \begin{cases} \beta(x) & x \neq y \\ d & x = y \end{cases}$$

Semantic Evaluation of Terms

Given a first-order state $\mathcal{S}$ and a variable assignment β
it is possible to evaluate first-order terms under $\mathcal{S}$ and β

Definition (Valuation of Terms)

$val_{\mathcal{S},\beta}$: Term $\rightarrow \mathcal{D}$ such that $val_{\mathcal{S},\beta}(t) \in \mathcal{D}^{\tau}$ for $t \in \text{Term}_{\tau}$:

- $val_{\mathcal{S},\beta}(x) = \beta(x)$
- $val_{\mathcal{S},\beta}(f(t_1, \ldots, t_r)) = \mathcal{I}(f)(val_{\mathcal{S},\beta}(t_1), \ldots, val_{\mathcal{S},\beta}(t_r))$

Semantic Evaluation of Terms Cont'd

Example

Signature: **int** `i`; **short** `j`; **int** `f`(**int**);

$\mathcal{D} = \{17, 2, o\}$ where all numbers are short

Variables: `Object obj`; **int** `x`;

$\mathcal{I}(\texttt{i}) = 17$
$\mathcal{I}(\texttt{j}) = 17$

$\mathcal{D}^{\textbf{int}}$	$\mathcal{I}(\texttt{f})$
2	17
17	2

Var	β
`obj`	o
`x`	17

- $val_{\mathcal{S},\beta}(\texttt{f(f(i))})$?
- $val_{\mathcal{S},\beta}(x)$?

Semantic Evaluation of Formulas

Definition (Valuation of Formulas)

$val_{\mathcal{S},\beta}(\phi)$ for $\phi \in For$

- $val_{\mathcal{S},\beta}(p(t_1, \ldots, t_r)) = T$ iff $(val_{\mathcal{S},\beta}(t_1), \ldots, val_{\mathcal{S},\beta}(t_r)) \in \mathcal{I}(p)$

Semantic Evaluation of Formulas

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$val_{\mathcal{S},\beta}(\phi)$ for $\phi \in For$

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- $val_{\mathcal{S},\beta}(\phi \wedge \psi) = T$ iff $val_{\mathcal{S},\beta}(\phi) = T$ and $val_{\mathcal{S},\beta}(\psi) = T$

Semantic Evaluation of Formulas

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$val_{\mathcal{S},\beta}(\phi)$ for $\phi \in For$

- $val_{\mathcal{S},\beta}(p(t_1, \ldots, t_r)) = T$ iff $(val_{\mathcal{S},\beta}(t_1), \ldots, val_{\mathcal{S},\beta}(t_r)) \in \mathcal{I}(p)$
- $val_{\mathcal{S},\beta}(\phi \wedge \psi) = T$ iff $val_{\mathcal{S},\beta}(\phi) = T$ and $val_{\mathcal{S},\beta}(\psi) = T$
- $\neg, \vee, \rightarrow, \leftrightarrow$ as in propositional logic

Semantic Evaluation of Formulas

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$val_{\mathcal{S},\beta}(\phi)$ for $\phi \in For$

- $val_{\mathcal{S},\beta}(p(t_1, \ldots, t_r)) = T$ iff $(val_{\mathcal{S},\beta}(t_1), \ldots, val_{\mathcal{S},\beta}(t_r)) \in \mathcal{I}(p)$
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- $\neg, \vee, \rightarrow, \leftrightarrow$ as in propositional logic
- $val_{\mathcal{S},\beta}(\forall\, \tau\ x;\ \phi) = T$ iff $val_{\mathcal{S},\beta_x^d}(\phi) = T$ for all $d \in \mathcal{D}^\tau$

Semantic Evaluation of Formulas

Definition (Valuation of Formulas)

$val_{\mathcal{S},\beta}(\phi)$ for $\phi \in For$

- $val_{\mathcal{S},\beta}(p(t_1,\ldots,t_r)) = T$ iff $(val_{\mathcal{S},\beta}(t_1),\ldots,val_{\mathcal{S},\beta}(t_r)) \in \mathcal{I}(p)$
- $val_{\mathcal{S},\beta}(\phi \wedge \psi) = T$ iff $val_{\mathcal{S},\beta}(\phi) = T$ and $val_{\mathcal{S},\beta}(\psi) = T$
- $\neg, \vee, \rightarrow, \leftrightarrow$ as in propositional logic
- $val_{\mathcal{S},\beta}(\forall\, \tau\ x;\ \phi) = T$ iff $val_{\mathcal{S},\beta_x^d}(\phi) = T$ for all $d \in \mathcal{D}^\tau$
- $val_{\mathcal{S},\beta}(\exists\, \tau\ x;\ \phi) = T$ iff $val_{\mathcal{S},\beta_x^d}(\phi) = T$ for at least one $d \in \mathcal{D}^\tau$

Semantic Evaluation of Formulas Cont'd

Example

Signature: **short** `j`; **int** `f(`**int**`)`; `Object obj`; `<(`**int**`,`**int**`)`;
$\mathcal{D} = \{17, 2, o\}$ where all numbers are short

$\mathcal{I}(j) = 17$
$\mathcal{I}(\texttt{obj}) = o$

$\mathcal{D}^{\textbf{int}}$	$\mathcal{I}(f)$
2	2
17	2

$\mathcal{D}^{\textbf{int}} \times \mathcal{D}^{\textbf{int}}$	in $\mathcal{I}(<)$?
$(2, 2)$	F
$(2, 17)$	T
$(17, 2)$	F
$(17, 17)$	F

- $val_{\mathcal{S},\beta}(f(j) < j)$?
- $val_{\mathcal{S},\beta}(\exists\, \textbf{int}\ x;\ f(x) = x)$?
- $val_{\mathcal{S},\beta}(\forall\, \texttt{Object}\ o1;\ \forall\, \texttt{Object}\ o2;\ o1 = o2)$?

Semantic Notions

Definition (Satisfiability, Truth, Validity)

$$\begin{array}{rlll} val_{\mathcal{S},\beta}(\phi) = T & & & (\phi \text{ is } \textbf{satisfiable}) \\ \mathcal{S} \models \phi & \text{iff} & \text{for all } \beta : val_{\mathcal{S},\beta}(\phi) = T & (\phi \text{ is } \textbf{true} \text{ in } \mathcal{S}) \\ \models \phi & \text{iff} & \text{for all } \mathcal{S} : \quad \mathcal{S} \models \phi & (\phi \text{ is } \textbf{valid}) \end{array}$$

Closed formulas that are satisfiable are also true: one top-level notion

Semantic Notions

Definition (Satisfiability, Truth, Validity)

$val_{\mathcal{S},\beta}(\phi) = T$			(ϕ is **satisfiable**)
$\mathcal{S} \models \phi$	iff	for all β : $val_{\mathcal{S},\beta}(\phi) = T$	(ϕ is **true** in $\mathcal{S}$)
$\models \phi$	iff	for all $\mathcal{S}$: $\mathcal{S} \models \phi$	(ϕ is **valid**)

Closed formulas that are satisfiable are also true: one top-level notion

Example

- $f(j) < j$ is true in $\mathcal{S}$
- $\exists\, \mathbf{int}\ x;\ i = x$ is valid
- $\exists\, \mathbf{int}\ x;\ \neg(x = x)$ is not satisfiable