Denotational Semantics

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Semantics for every season

Operational semantics	How a program operates
Denotational semantics	What a program is
Axiomatic semantics	Which logical properties a program satisfies

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Compiler correctness and contextual equivalence

We adopted the following notion of equivalence

$$\mathtt{p} \equiv_o \mathtt{q} \text{ iff } \Big(\text{for every } \sigma.\ \langle \mathtt{p}, \sigma \rangle \Downarrow \sigma' \text{ iff } \langle \mathtt{q}, \sigma \rangle \Downarrow \sigma'\Big)$$

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Compilers adopt the stronger version

$$\mathrm{p} \equiv \mathrm{q} \text{ iff } \Big(\text{for every context } C.\ C[\mathrm{p}] \equiv_o C[\mathrm{q}]\Big)$$

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Compilers adopt the stronger version

$$\mathrm{p} \equiv \mathrm{q} \text{ iff } \Big(\text{for every context } C.\ C[\mathrm{p}] \equiv_o C[\mathrm{q}]\Big)$$

$\boxed{\text{Why is that ?}}$

Contextual equivalence

Contexts

$C ::= [-] \mid C \wedge \mathtt{b} \mid \mathtt{b} \wedge C \mid \neg C$

Exercise

Prove the equivalence $\mathtt{b}_1 \equiv_o \mathtt{b}_2 \iff \mathtt{b}_1 \equiv \mathtt{b}_2$

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Prove the equivalence $\mathtt{b}_1 \equiv_o \mathtt{b}_2 \iff \mathtt{b}_1 \equiv \mathtt{b}_2$

Homework: repeat the exercise now for arithmetic expressions

Contextual equivalence

Contexts

$C ::= [-] \mid C \,\texttt{;}\, \mathtt{p} \mid \texttt{if}\ \mathtt{b}\ \texttt{then}\ C\ \texttt{else}\ \mathtt{p} \mid \texttt{while}\ \mathtt{b}\ \texttt{do}\ \{\ C\ \} \mid \ldots$

Contextual equivalence

Contexts

$C ::= [-] \mid C \, ; \mathrm{p} \mid \texttt{if}\ \mathrm{b}\ \texttt{then}\ C\ \texttt{else}\ \mathrm{p} \mid \texttt{while}\ \mathrm{b}\ \texttt{do}\ \{\ C\ \} \mid \ldots$

$\boxed{\text{Can we still prove } \mathrm{p} \equiv_o \mathrm{q} \iff \mathrm{p} \equiv \mathrm{q} \text{ ?}}$

Next challenge: programs as part of a mathematical theory

$$\boxed{\text{Programming language}} \quad \hookrightarrow \quad \boxed{\text{Mathematical theory}}$$

The latter include *e.g.*

- functions (recall program calculus)
- linear algebra
- relations
- domain theory (theory of computability and beyond)
- ...

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Boolean terms and their denotational semantics

$$\mathtt{b} ::= \mathtt{x} \mid \mathtt{b} \wedge \mathtt{b} \mid \neg \mathtt{b}$$

Terms interpreted as functions $[\![\mathtt{b}]\!] : \mathit{State} \to 2$

Term operations interpreted via the boolean algebra 2

$$[\![\mathtt{x}]\!](\sigma) = \sigma(\mathtt{x})$$

$$[\![\mathtt{b}_1 \wedge \mathtt{b}_2]\!] = (\wedge) \cdot \langle [\![\mathtt{b}_1]\!], [\![\mathtt{b}_2]\!] \rangle$$

$$[\![\neg \mathtt{b}]\!] = (\neg) \cdot [\![\mathtt{b}]\!]$$

The relation between big-step and denotational semantics

Theorem

For every term $\mathtt{b}$ *and memory* σ *we have* $\langle \mathtt{b}, \sigma \rangle \Downarrow v$ *iff* $[\![\mathtt{b}]\!](\sigma) = v$

Proof.

Straightforward induction $\square$

Corollary

$\mathtt{b}_1 \equiv \mathtt{b}_2$ *iff* $\mathtt{b}_1 \equiv_o \mathtt{b}_2$ *iff* $[\![\mathtt{b}_1]\!] = [\![\mathtt{b}_2]\!]$

Profits!

We can now reduce checking for equivalence to ...

<u>Program calculus</u> and <u>Boolean algebra</u>

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We can now reduce checking for equivalence to . . .

Program calculus and Boolean algebra

Example

$$
\begin{aligned}
[\![\mathtt{b}_1 \wedge \mathtt{b}_2]\!] &= (\wedge) \cdot \langle [\![\mathtt{b}_1]\!], [\![\mathtt{b}_2]\!] \rangle \\
&= (\wedge) \cdot \mathrm{sw} \cdot \langle [\![\mathtt{b}_1]\!], [\![\mathtt{b}_2]\!] \rangle \\
&= (\wedge) \cdot \langle \pi_2, \pi_1 \rangle \cdot \langle [\![\mathtt{b}_1]\!], [\![\mathtt{b}_2]\!] \rangle \\
&= (\wedge) \cdot \langle \pi_2 \cdot \langle [\![\mathtt{b}_1]\!], [\![\mathtt{b}_2]\!] \rangle, \pi_1 \cdot \langle [\![\mathtt{b}_1]\!], [\![\mathtt{b}_2]\!] \rangle \rangle \\
&= (\wedge) \cdot \langle [\![\mathtt{b}_2]\!], [\![\mathtt{b}_1]\!] \rangle \\
&= [\![\mathtt{b}_2 \wedge \mathtt{b}_1]\!]
\end{aligned}
$$

Exercises

1. Show that $\mathtt{b} \wedge \mathtt{b} \equiv \mathtt{b}$ via the denotational semantics
2. Define a denotational semantics for arithmetic expressions e
3. Prove that $[\![\mathsf{e}_1 + \mathsf{e}_2]\!] = [\![\mathsf{e}_2 + \mathsf{e}_1]\!]$
4. Prove the equivalence $\langle \mathsf{e}, \sigma \rangle \Downarrow v$ iff $[\![\mathsf{e}]\!](\sigma) = v$

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Key takeaways

Programs interpreted as functions $[\![\mathrm{p}]\!] : State_\perp \to State_\perp$

$State_\perp = State \cup \{\perp\}$ where $\perp$ represents non-termination

Sequential composition is function composition

Programs and their denotational semantics

$$\mathtt{p} ::= \mathtt{x} := \mathtt{e} \mid \mathtt{p}\ ;\ \mathtt{p} \mid \mathtt{if}\ \mathtt{b}\ \mathtt{then}\ \mathtt{p}\ \mathtt{else}\ \mathtt{p} \mid \mathtt{while}\ \mathtt{b}\ \mathtt{do}\ \{\ \mathtt{p}\ \}$$

$$\begin{aligned}
[\![\mathtt{x} := \mathtt{e}]\!] &= \sigma \mapsto \sigma[[\![\mathtt{e}]\!]/\mathtt{x}] \\
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[\![\mathtt{while}\ \mathtt{b}\ \mathtt{do}\ \{\ \mathtt{p}\ \}]\!] &= \ \ldots\ldots
\end{aligned}$$

The relation between big-step and denotational semantics

Danger, Will Robinson: no while-loops yet ...

Theorem

For every p *and* σ *we have* $\langle \mathrm{p}, \sigma \rangle \Downarrow \sigma'$ *iff* $[\![\mathrm{p}]\!](\sigma) = \sigma'$

Proof.

Straightforward induction $\square$

Corollary

$\mathrm{p} \equiv \mathrm{q}$ *iff* $\mathrm{p} \equiv_o \mathrm{q}$ *iff* $[\![\mathrm{p}]\!] = [\![\mathrm{q}]\!]$

Profits!

Recall when we had to prove the two equivalences

- $(\mathtt{p} \mathbin{;} \mathtt{q}) \mathbin{;} \mathtt{r} \equiv \mathtt{p} \mathbin{;} (\mathtt{q} \mathbin{;} \mathtt{r})$
- $(\mathtt{if}\ \mathtt{b}\ \mathtt{then}\ \mathtt{p}\ \mathtt{else}\ \mathtt{q}) \mathbin{;} \mathtt{r} \equiv \mathtt{if}\ \mathtt{b}\ \mathtt{then}\ \mathtt{p} \mathbin{;} \mathtt{r}\ \mathtt{else}\ \mathtt{q} \mathbin{;} \mathtt{r}$

with the big-step semantics

Show the same via the denotational semantics

Programs and a (tentative) denotational semantics

$$\mathtt{p} ::= \mathtt{x} := \mathtt{e} \mid \mathtt{p} \mathbin{\texttt{;}} \mathtt{p} \mid \texttt{if}\ \mathtt{b}\ \texttt{then}\ \mathtt{p}\ \texttt{else}\ \mathtt{p} \mid \texttt{while}\ \mathtt{b}\ \texttt{do}\ \{\ \mathtt{p}\ \}$$

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\end{aligned}$$

I'm very clear, Brexit does mean brexit

(Theresa May) `https://www.youtube.com/watch?v=oRDfFJAu6Bo`

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Partially ordered set

Definition (Poset)

A set with a reflexive, anti-symmetric, and transitive relation $\leq$

Examples

- $(\mathbb{N},$ the usual order $\leq$ on natural numbers$)$
- $(\mathbb{R},$ the usual order $\leq$ on the real numbers$)$
- $(X, =)$ (for any set X)

Partially ordered set

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In our context $x \leq y$ reads as

y more informative than x

New posets from old ones

Addition of a bottom element

If $(X, \leq_X)$ is a poset then $(X_\perp, \leq)$ is a poset when defined as

- $x_1 \leq x_2$ iff $x_1 \leq_X x_2$
- $\perp \leq x$ (for all $x \in X$)

$\perp$ is the least informative element, akin to non-termination

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$\perp$ is the least informative element, akin to non-termination

Example

In what way is $State_\perp$ a poset ?

Data aggregation

We will often wish to collect an increasing seq. of information

$$x_1 \leq x_2 \leq x_3 \leq \dots$$

into a single datum, denoted by $\bigvee_{i \in \mathbb{N}} x_i$

Data aggregation

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into a single datum, denoted by $\bigvee_{i \in \mathbb{N}} x_i$

This element should be more informative than any x_j ($j \in \mathbb{N}$), *i.e.*

$$x_j \leq \bigvee_{i \in \mathbb{N}} x_i$$

and contain no more information than the one in the chain, *i.e.*

$$(\forall j \in \mathbb{N}.\, x_j \leq y) \Longrightarrow \bigvee_{i \in \mathbb{N}} x_i \leq y$$

Posets + Data aggregation

Definition (ω-CPO)

A poset with data aggregation as previously described

Examples

- $\mathbb{N}$ is <u>not</u> an ω-CPO but $\mathbb{N} \cup \{\infty\}$ is
- $\mathbb{R}$ is <u>not</u> an ω-CPO but $\mathbb{R} \cup \{\infty\}$ and $[0, 1]$ are

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Exercise

Show that $\mathit{State}_\perp$ is an ω-CPO

Maps between ω-CPOs

We wish them to represent some form of computability . . .

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Maps between ω-CPOs

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. . . and thus we cannot allow all maps

We enforce instead the following laws

$$f(\vee_n x_n) = \vee_n f(x_n) \qquad \text{(continuity)}$$

$$x_1 \leq x_2 \Rightarrow f(x_1) \leq f(x_2) \qquad \text{(monotonicity)}$$

Continuity $\simeq$ Computability ?

What does it mean for $p : X \to \{\bot \leq \top\}$ to be continuous ?

Suppose $x \in X$ is given by a chain of finite approximations

$$x_1 \leq x_2 \leq x_3 \ldots$$

... then deduce that

$$\begin{aligned} p(\textstyle\bigvee_{n\in\mathbb{N}} x_n) = \top &\iff \textstyle\bigvee_{n\in\mathbb{N}} p(x_n) = \top \\ &\iff \exists n \in \mathbb{N}.\, p(x_n) = \top \end{aligned}$$

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i.e. that p terminates with `tt` for x iff p can evaluate a finite approximation of x to `tt`

Continuity $\simeq$ Computability ?

Exercise 1

Show that $(\mathcal{P}(\mathbb{N}), \subseteq)$ is an ω-CPO

Exercise 2

Can $\texttt{isInfinite} : \mathcal{P}(\mathbb{N}) \to \{\bot \leq \top\}$ be continuous ?

$$
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$\boxed{\text{Are all programs } [\![\mathtt{p}]\!] \text{ continuous ?}}$

Continuity $\simeq$ Computability ?

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$\boxed{\text{Are all programs } \llbracket \mathrm{p} \rrbracket \text{ continuous ?}}$

Yes !! Just use program calculus ‘with continuous functions’

Fixpoints for while-loops

Definition

An element $x \in X$ is a fixpoint of $f : X \to X$ if $f(x) = x$

A notion with applications in different fields

- economics (game theory)
- dynamical systems (equilibrium points)
- automata theory
- essentially everywhere ...

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Here while-loops will be fixpoints

Fixpoints for while-loops

$\boxed{\text{... but a fixpoint of which function ?}}$

Fixpoints for while-loops

$\boxed{\ldots \text{ but a fixpoint of which function ?}}$

Recall our previous idea

$$[\![\mathtt{while}\, \mathtt{b}\, \mathtt{do}\, \{\, \mathtt{p}\, \}]\!] = [[\![\mathtt{while}\, \mathtt{b}\, \mathtt{do}\, \{\, \mathtt{p}\, \}]\!] \cdot [\![\mathrm{p}]\!], \mathrm{id}] \cdot \mathrm{dist} \cdot \langle [\![\mathtt{b}]\!], \mathrm{id} \rangle$$

It translates to saying that $[\![\mathtt{while}\, \mathtt{b}\, \mathtt{do}\, \{\, \mathtt{p}\, \}]\!]$ is a fixpoint of

$$k \longmapsto [k \cdot [\![\mathrm{p}]\!], \mathrm{id}] \cdot \mathrm{dist} \cdot \langle [\![\mathtt{b}]\!], \mathrm{id} \rangle$$

The least fixpoint theorem

Theorem

Every continuous, monotone map $f : X \to X$ has a least fixpoint

$$\mathrm{lfp}\ f = \vee_{n \in \mathbb{N}} f^n(\bot)$$

Exercise

Prove the theorem

The least fixpoint theorem

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Exercise

Prove the theorem

And finally . . .

Programs and a denotational semantics

$$\mathtt{p} ::= \mathtt{x} := \mathtt{e} \mid \mathtt{p}\ ;\ \mathtt{p} \mid \mathtt{if}\ \mathtt{b}\ \mathtt{then}\ \mathtt{p}\ \mathtt{else}\ \mathtt{p} \mid \mathtt{while}\ \mathtt{b}\ \mathtt{do}\ \{\ \mathtt{p}\ \}$$

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$$[\![\mathtt{while}\ \mathtt{b}\ \mathtt{do}\ \{\ \mathtt{p}\ \}]\!] = \mathrm{lfp}\ \Big(k \mapsto [k \cdot [\![\mathtt{p}]\!], \mathrm{id}] \cdot \mathrm{dist} \cdot \langle [\![\mathtt{b}]\!], \mathrm{id} \rangle\Big)$$

The semantics at work

Prove the following equivalences

- $\texttt{while}\, \mathtt{b}\, \{\mathtt{p}\} \equiv \texttt{if}\, \mathtt{b}\, \texttt{then}\, \mathtt{p}\, \texttt{else}\, \mathtt{skip}$
- $\texttt{while}\, \mathtt{b}\, \{\mathtt{p}\}\, ;\, \mathtt{q} \equiv \texttt{if}\, \mathtt{b}\, \texttt{then}\, \mathtt{p}\, ;\, \texttt{while}\, \mathtt{b}\, \{\mathtt{p}\}\, \texttt{else}\, \mathtt{q}$
- $\texttt{while}\, \mathtt{ff}\, \{\mathtt{p}\}\, ;\, \mathtt{q} \equiv \mathtt{q}$
- $\texttt{while}\, \mathtt{tt}\, \{\mathtt{p}\} \equiv \texttt{while}\, \mathtt{tt}\, \{\mathtt{q}\}$

The semantics at work

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- $\texttt{while}\ \mathtt{ff}\ \{\mathrm{p}\}\ ;\ \mathrm{q} \equiv \mathrm{q}$
- $\texttt{while}\ \mathtt{tt}\ \{\mathrm{p}\} \equiv \texttt{while}\ \mathtt{tt}\ \{\mathrm{q}\}$

Prove the following implication

$$[\![\mathrm{p}]\!] = [\![\mathrm{q}]\!] \Longrightarrow \text{for all contexts } C.\, [\![C[\mathrm{p}]]\!] = [\![C[\mathrm{q}]]\!]$$

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Theorem

For every $\mathtt{p}$ *and* σ *we have* $\langle \mathtt{p}, \sigma \rangle \Downarrow \sigma'$ *iff* $[\![\mathtt{p}]\!](\sigma) = \sigma'$

Corollary

$\mathtt{p} \equiv_o \mathtt{q}$ *iff* $[\![\mathtt{p}]\!] = [\![\mathtt{q}]\!]$

Corollary (Full abstraction)

$[\![\mathtt{p}]\!] = [\![\mathtt{q}]\!]$ *iff* $\forall C.\, [\![C[\mathtt{p}]]\!] = [\![C[\mathtt{q}]]\!]$ *iff* $\forall C.\, C[\mathtt{p}] \equiv_o C[\mathtt{q}]$ *iff* $\mathtt{p} \equiv \mathtt{q}$