



Semantics and Verification of Software

Winter Semester 2017/18

Lecture 7: Denotational Semantics of WHILE II (Fixpoint Theory)

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<http://moves.rwth-aachen.de/teaching/ws-1718/sv-sw/>

Recap: The Denotational Approach

Outline of Lecture 7

Recap: The Denotational Approach

Chain-Complete Partial Orders

Monotonic and Continuous Functions

The Fixpoint Theorem

Recap: The Denotational Approach

Semantics of Statements I

Definition (Denotational semantics of statements)

The (denotational) semantic functional for statements,

$$\mathcal{E}[\cdot] : \text{Cmd} \rightarrow (\Sigma \dashrightarrow \Sigma),$$

is given by:

$$\begin{aligned}\mathcal{E}[\text{skip}] &:= \text{id}_\Sigma \\ \mathcal{E}[x := a]\sigma &:= \sigma[x \mapsto \mathcal{A}[a]\sigma] \\ \mathcal{E}[c_1; c_2] &:= \mathcal{E}[c_2] \circ \mathcal{E}[c_1] \\ \mathcal{E}[\text{if } b \text{ then } c_1 \text{ else } c_2 \text{ end}] &:= \text{cond}(\mathcal{B}[b], \mathcal{E}[c_1], \mathcal{E}[c_2]) \\ \mathcal{E}[\text{while } b \text{ do } c \text{ end}] &:= \text{fix}(\Phi)\end{aligned}$$

where $\Phi : (\Sigma \dashrightarrow \Sigma) \rightarrow (\Sigma \dashrightarrow \Sigma) : f \mapsto \text{cond}(\mathcal{B}[b], f \circ \mathcal{E}[c], \text{id}_\Sigma)$

Recap: The Denotational Approach

Characterisation of $\text{fix}(\Phi)$ I

Now $\text{fix}(\Phi)$ can be characterised by:

- $\text{fix}(\Phi)$ is a **fixpoint** of Φ , i.e.,

$$\Phi(\text{fix}(\Phi)) = \text{fix}(\Phi)$$

- $\text{fix}(\Phi)$ is **minimal** with respect to \sqsubseteq , i.e., for every $f_0 : \Sigma \dashrightarrow \Sigma$ such that $\Phi(f_0) = f_0$,

$$\text{fix}(\Phi) \sqsubseteq f_0$$

Example

For `while true do skip end` we obtain for every $f : \Sigma \dashrightarrow \Sigma$:

$$\Phi(f) = \text{cond}(\mathfrak{B}[\text{true}], f \circ \mathcal{C}[\text{skip}], \text{id}_\Sigma) = f$$

$\Rightarrow \text{fix}(\Phi) = f_\emptyset$ where $f_\emptyset(\sigma) := \text{undefined}$ for every $\sigma \in \Sigma$ (that is, $\text{graph}(f_\emptyset) = \emptyset$)

Recap: The Denotational Approach

Characterisation of $\text{fix}(\Phi)$ II

Goals:

- Prove **existence** of $\text{fix}(\Phi)$ for $\Phi(f) = \text{cond}(\mathcal{B}[[b]], f \circ \mathcal{C}[[c]], \text{id}_\Sigma)$
- Show how it can be “computed” (more exactly: **approximated**)

Sufficient conditions:

on domain $\Sigma \dashrightarrow \Sigma$: **chain-complete partial order**

on function Φ : **monotonicity** and **continuity**

Chain-Complete Partial Orders

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Chain-Complete Partial Orders

Partial Orders

Definition 7.1 (Partial order)

A **partial order (PO)** (D, \sqsubseteq) consists of a set D , called **domain**, and of a relation $\sqsubseteq \subseteq D \times D$ such that, for every $d_1, d_2, d_3 \in D$,

reflexivity: $d_1 \sqsubseteq d_1$

transitivity: $d_1 \sqsubseteq d_2$ and $d_2 \sqsubseteq d_3 \Rightarrow d_1 \sqsubseteq d_3$

antisymmetry: $d_1 \sqsubseteq d_2$ and $d_2 \sqsubseteq d_1 \Rightarrow d_1 = d_2$

It is called **total** if, in addition, always $d_1 \sqsubseteq d_2$ or $d_2 \sqsubseteq d_1$.

Chain-Complete Partial Orders

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Example 7.2

1. (\mathbb{N}, \leq) is a total partial order

Chain-Complete Partial Orders

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1. (\mathbb{N}, \leq) is a total partial order
2. $(2^{\mathbb{N}}, \subseteq)$ is a (non-total) partial order

Chain-Complete Partial Orders

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1. (\mathbb{N}, \leq) is a total partial order
2. $(2^{\mathbb{N}}, \subseteq)$ is a (non-total) partial order
3. $(\mathbb{N}, <)$ is not a partial order

Chain-Complete Partial Orders

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Example 7.2

1. (\mathbb{N}, \leq) is a total partial order
2. $(2^{\mathbb{N}}, \subseteq)$ is a (non-total) partial order
3. $(\mathbb{N}, <)$ is not a partial order (since not reflexive)

Chain-Complete Partial Orders

Application to $\text{fix}(\Phi)$

Lemma 7.3

$(\Sigma \dashrightarrow \Sigma, \sqsubseteq)$ is a partial order.

Chain-Complete Partial Orders

Application to $\text{fix}(\Phi)$

Lemma 7.3

$(\Sigma \dashrightarrow \Sigma, \sqsubseteq)$ is a partial order.

Proof.

Using the equivalence $f \sqsubseteq g \iff \text{graph}(f) \subseteq \text{graph}(g)$ and the partial-order property of \subseteq □

Chain-Complete Partial Orders

Chains and Least Upper Bounds I

Definition 7.4 (Chain, (least) upper bound)

Let (D, \sqsubseteq) be a partial order and $S \subseteq D$.

1. S is called a **chain** in D if, for every $s_1, s_2 \in S$,

$$s_1 \sqsubseteq s_2 \text{ or } s_2 \sqsubseteq s_1$$

(that is, S is a totally ordered subset of D).

Chain-Complete Partial Orders

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Chain-Complete Partial Orders

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(that is, S is a totally ordered subset of D).

2. An element $d \in D$ is called an **upper bound** of S if $s \sqsubseteq d$ for every $s \in S$ (notation: $S \sqsubseteq d$).
3. An upper bound d of S is called **least upper bound (LUB)** or **supremum** of S if $d \sqsubseteq d'$ for every upper bound d' of S (notation: $d = \bigsqcup S$).

Chains and Least Upper Bounds II

Example 7.5

1. Every subset $S \subseteq \mathbb{N}$ is a chain in (\mathbb{N}, \leq) .
It has a LUB (its greatest element) iff it is finite.

Chains and Least Upper Bounds II

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2. $\{\emptyset, \{0\}, \{0, 1\}, \dots\}$ is a chain in $(2^{\mathbb{N}}, \subseteq)$ with LUB \mathbb{N} .

Chain-Complete Partial Orders

Chains and Least Upper Bounds II

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It has a LUB (its greatest element) iff it is finite.
2. $\{\emptyset, \{0\}, \{0, 1\}, \dots\}$ is a chain in $(2^{\mathbb{N}}, \subseteq)$ with LUB \mathbb{N} .
3. Let $x \in \text{Var}$, and let $f_i : \Sigma \dashrightarrow \Sigma$ for every $i \in \mathbb{N}$ be given by

$$f_i(\sigma) := \begin{cases} \sigma[x \mapsto \sigma(x) + 1] & \text{if } \sigma(x) \leq i \\ \text{undefined} & \text{otherwise} \end{cases}$$

Then $\{f_0, f_1, f_2, \dots\}$ is a chain in $(\Sigma \dashrightarrow \Sigma, \sqsubseteq)$, since for every $i \in \mathbb{N}$ and $\sigma, \sigma' \in \Sigma$:

$$\begin{aligned} f_i(\sigma) &= \sigma' \\ \Rightarrow \sigma(x) \leq i, \sigma' &= \sigma[x \mapsto \sigma(x) + 1] \\ \Rightarrow \sigma(x) \leq i + 1, \sigma' &= \sigma[x \mapsto \sigma(x) + 1] \\ \Rightarrow f_{i+1}(\sigma) &= \sigma' \\ \Rightarrow f_i &\sqsubseteq f_{i+1} \end{aligned}$$

Chain-Complete Partial Orders

Chain Completeness

Definition 7.6 (Chain completeness)

A partial order is called **chain complete (CCPO)** if each of its chains has a least upper bound.

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Example 7.7

1. $(2^{\mathbb{N}}, \subseteq)$ is a CCPO with $\bigsqcup S = \bigcup_{M \in S} M$ for every chain $S \subseteq 2^{\mathbb{N}}$.

Chain-Complete Partial Orders

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2. (\mathbb{N}, \leq) is not chain complete

Chain-Complete Partial Orders

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1. $(2^{\mathbb{N}}, \subseteq)$ is a CCPO with $\bigsqcup S = \bigcup_{M \in S} M$ for every chain $S \subseteq 2^{\mathbb{N}}$.
2. (\mathbb{N}, \leq) is not chain complete (since, e.g., the chain \mathbb{N} has no upper bound).

Chain-Complete Partial Orders

Least Elements in CCPOs

Corollary 7.8

Every CCPO has a least element $\sqcup \emptyset$.

Chain-Complete Partial Orders

Least Elements in CCPOs

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Every CCPO has a least element $\sqcup \emptyset$.

Proof.

Let (D, \sqsubseteq) be a CCPO.

- By definition, \emptyset is a chain in D .

Chain-Complete Partial Orders

Least Elements in CCPOs

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Every CCPO has a least element $\sqcup \emptyset$.

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Let (D, \sqsubseteq) be a CCPO.

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- By definition, every $d \in D$ is an upper bound of \emptyset .

Chain-Complete Partial Orders

Least Elements in CCPOs

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Every CCPO has a least element $\sqcup \emptyset$.

Proof.

Let (D, \sqsubseteq) be a CCPO.

- By definition, \emptyset is a chain in D .
- By definition, every $d \in D$ is an upper bound of \emptyset .
- Thus $\sqcup \emptyset$ exists and is the least element of D .



Chain-Complete Partial Orders

Application to $\text{fix}(\Phi)$

Lemma 7.9

- $(\Sigma \dashrightarrow \Sigma, \sqsubseteq)$ is a CCPO with least element f_\emptyset where $\text{graph}(f_\emptyset) = \emptyset$.
- In particular, for every chain $S \subseteq \Sigma \dashrightarrow \Sigma$, $\text{graph}(\bigsqcup S) = \bigcup_{f \in S} \text{graph}(f)$.

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Proof.

on the board



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Proof.

on the board □

Example 7.10 (cf. Example 7.5(3))

Let $x \in \text{Var}$, and let $f_i : \Sigma \dashrightarrow \Sigma$ for every $i \in \mathbb{N}$ be given by

$$f_i(\sigma) := \begin{cases} \sigma[x \mapsto \sigma(x) + 1] & \text{if } \sigma(x) \leq i \\ \text{undefined} & \text{otherwise} \end{cases}$$

Then $S := \{f_0, f_1, f_2, \dots\}$ is a chain (cf. Example 7.5(3)) with $\bigsqcup S = f$ where

$$f : \Sigma \rightarrow \Sigma : \sigma \mapsto \sigma[x \mapsto \sigma(x) + 1]$$

Monotonic and Continuous Functions

Outline of Lecture 7

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Monotonic and Continuous Functions

Monotonicity I

Definition 7.11 (Monotonicity)

Let (D, \sqsubseteq) and (D', \sqsubseteq') be partial orders, and let $F : D \rightarrow D'$. F is called **monotonic** (w.r.t. (D, \sqsubseteq) and (D', \sqsubseteq')) if, for every $d_1, d_2 \in D$,

$$d_1 \sqsubseteq d_2 \Rightarrow F(d_1) \sqsubseteq' F(d_2).$$

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Interpretation: monotonic functions “preserve information”

Monotonic and Continuous Functions

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Interpretation: monotonic functions “preserve information”

Example 7.12

1. Let $T := \{S \subseteq \mathbb{N} \mid S \text{ finite}\}$. Then $F_1 : T \rightarrow \mathbb{N} : S \mapsto \sum_{n \in S} n$ is monotonic w.r.t. $(2^{\mathbb{N}}, \subseteq)$ and (\mathbb{N}, \leq) .

Monotonic and Continuous Functions

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1. Let $T := \{S \subseteq \mathbb{N} \mid S \text{ finite}\}$. Then $F_1 : T \rightarrow \mathbb{N} : S \mapsto \sum_{n \in S} n$ is monotonic w.r.t. $(2^{\mathbb{N}}, \subseteq)$ and (\mathbb{N}, \leq) .
2. $F_2 : 2^{\mathbb{N}} \rightarrow 2^{\mathbb{N}} : S \mapsto \mathbb{N} \setminus S$ is not monotonic w.r.t. $(2^{\mathbb{N}}, \subseteq)$ (since, e.g., $\emptyset \subseteq \mathbb{N}$ but $F_2(\emptyset) = \mathbb{N} \not\subseteq F_2(\mathbb{N}) = \emptyset$).

Monotonic and Continuous Functions

Application to $\text{fix}(\Phi)$

Lemma 7.13

Let $b \in BExp$, $c \in Cmd$, and $\Phi : (\Sigma \dashrightarrow \Sigma) \rightarrow (\Sigma \dashrightarrow \Sigma)$ with $\Phi(f) := \text{cond}(\mathcal{B}[[b]], f \circ \mathcal{C}[[c]], \text{id}_\Sigma)$. Then Φ is monotonic w.r.t. $(\Sigma \dashrightarrow \Sigma, \sqsubseteq)$.

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Proof.

on the board □

Monotonic and Continuous Functions

Monotonicity II

The following lemma states how chains behave under monotonic functions.

Lemma 7.14

Let (D, \sqsubseteq) and (D', \sqsubseteq') be CCPOs, $F : D \rightarrow D'$ monotonic, and $S \subseteq D$ a chain in D .
Then:

1. $F(S) := \{F(d) \mid d \in S\}$ is a chain in D' .
2. $\bigsqcup F(S) \sqsubseteq' F(\bigsqcup S)$.

Monotonic and Continuous Functions

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Proof.

on the board □

Monotonic and Continuous Functions

Continuity

A function F is continuous if applying F and taking LUBs is commutable:

Definition 7.15 (Continuity)

Let (D, \sqsubseteq) and (D', \sqsubseteq') be CCPOs and $F : D \rightarrow D'$ monotonic. Then F is called **continuous** (w.r.t. (D, \sqsubseteq) and (D', \sqsubseteq')) if, for every non-empty chain $S \subseteq D$,

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Lemma 7.16

Let $b \in BExp$, $c \in Cmd$, and $\Phi(f) := \text{cond}(\mathfrak{B}[[b]], f \circ \mathfrak{C}[[c]], \text{id}_\Sigma)$. Then Φ is continuous w.r.t. $(\Sigma \dashrightarrow \Sigma, \sqsubseteq)$.

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Proof.

omitted □

The Fixpoint Theorem

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The Fixpoint Theorem



Alfred Tarski (1901–1983)



Bronislaw Knaster (1893–1990)

Theorem 7.17 (Fixpoint Theorem by Tarski and Knaster)

Let (D, \sqsubseteq) be a CCPO and $F : D \rightarrow D$ continuous. Then

$$\text{fix}(F) := \bigsqcup \left\{ F^n \left(\bigsqcup \emptyset \right) \mid n \in \mathbb{N} \right\}$$

is the **least fixpoint** of F where $F^0(d) := d$ and $F^{n+1}(d) := F(F^n(d))$.

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Proof.

on the board



The Fixpoint Theorem

An Example

Example 7.18

- **Domain:** $(2^{\mathbb{N}}, \subseteq)$ (CCPO with $\bigsqcup S = \bigcup_{N \in S} N$ – see Example 7.7)

The Fixpoint Theorem

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Example 7.18

- **Domain:** $(2^{\mathbb{N}}, \subseteq)$ (CCPO with $\bigsqcup S = \bigcup_{N \in S} N$ – see Example 7.7)
- **Function:** $F : 2^{\mathbb{N}} \rightarrow 2^{\mathbb{N}} : N \mapsto N \cup A$ for some fixed $A \subseteq \mathbb{N}$
 - F monotonic: $M \subseteq N \Rightarrow F(M) = M \cup A \subseteq N \cup A = F(N)$
 - F continuous: $F(\bigsqcup S) = F(\bigcup_{N \in S} N) = (\bigcup_{N \in S} N) \cup A = \bigcup_{N \in S} (N \cup A) = \bigcup_{N \in S} F(N) = \bigsqcup F(S)$

The Fixpoint Theorem

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Example 7.18

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- **Fixpoint iteration:** $N_n := F^n(\bigsqcup \emptyset)$ where $\bigsqcup \emptyset = \emptyset$
 - $N_0 = \bigsqcup \emptyset = \emptyset$
 - $N_1 = F(N_0) = \emptyset \cup A = A$
 - $N_2 = F(N_1) = A \cup A = A = N_n$ for every $n \geq 1$ $\Rightarrow \text{fix}(F) = A$

The Fixpoint Theorem

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Example 7.18

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- **Function:** $F : 2^{\mathbb{N}} \rightarrow 2^{\mathbb{N}} : N \mapsto N \cup A$ for some fixed $A \subseteq \mathbb{N}$
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- **Fixpoint iteration:** $N_n := F^n(\bigsqcup \emptyset)$ where $\bigsqcup \emptyset = \emptyset$
 - $N_0 = \bigsqcup \emptyset = \emptyset$
 - $N_1 = F(N_0) = \emptyset \cup A = A$
 - $N_2 = F(N_1) = A \cup A = A = N_n$ for every $n \geq 1$ $\Rightarrow \text{fix}(F) = A$
- **Alternatively:** $F(N) := N \cap A$ $\Rightarrow \text{fix}(F) = \emptyset$