We have now seen two operational models for programming languages: small-step and large-step. In this lecture, we consider a different semantic model, called denotational semantics.

The idea in denotational semantics is to express the meaning of a program as the mathematical function that expresses what the program computes. We can think of an IMP program $c$ as a function from stores to stores: given an an initial store, the program produces a final store. For example, the program $\text{foo} := \text{bar} + 1$ can be thought of as a function that when given an input store $\sigma$, produces a final store $\sigma'$ that is identical to $\sigma$ except that it maps foo to the integer $\sigma(\text{bar}) + 1$; that is, $\sigma' = \sigma[\text{foo} \mapsto \sigma(\text{bar}) + 1]$. We will model programs as functions from input stores to output stores. As opposed to operational models, which tell us how programs execute, the denotational model shows us what programs compute.

1 A Denotational Semantics for IMP

For each program $c$, we write $\mathcal{C}[c]$ for the denotation of $c$, that is, the mathematical function that $c$ represents:

$$\mathcal{C}[c] : \text{Store} \rightarrow \text{Store}.$$  

Note that $\mathcal{C}[c]$ is actually a partial function (as opposed to a total function), both because the store may not be defined on the free variables of the program and because program may not terminate for certain input stores. The function $\mathcal{C}[c]$ is not defined for non-terminating programs as they have no corresponding output stores.

We will write $\mathcal{C}[c] \sigma$ for the result of applying the function $\mathcal{C}[c]$ to the store $\sigma$. That is, if $f$ is the function that $\mathcal{C}[c]$ denotes, then we write $\mathcal{C}[c] \sigma$ to mean the same thing as $f(\sigma)$.

We must also model expressions as functions, this time from stores to the values they represent. We will write $\mathcal{A}[a]$ for the denotation of arithmetic expression $a$, and $\mathcal{B}[b]$ for the denotation of boolean expression $b$.

$$\mathcal{A}[a] : \text{Store} \rightarrow \text{Int}$$  

$$\mathcal{B}[b] : \text{Store} \rightarrow \{\text{true, false}\}$$  

Now we want to define these functions. To make it easier to write down these definitions, we will describe (partial) functions using sets of pairs. More precisely, we will represent a partial map $f : A \rightarrow B$ as a set of pairs $F = \{(a, b) \mid a \in A \text{ and } b = f(a) \in B\}$ such that, for each $a \in A$, there is at most one pair of the form $(a, \cdot)$ in the set. Hence $(a, b) \in F$ is the same as $b = f(a)$. 

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We can now define denotations for IMP. We start with the denotations of expressions:

\[ A[n] = \{(\sigma, n)\} \]
\[ A[x] = \{(\sigma, \sigma(x))\} \]
\[ A[a_1 + a_2] = \{(\sigma, n) \mid (\sigma, n_1) \in A[a_1] \land (\sigma, n_2) \in A[a_2] \land n = n_1 + n_2\} \]

\[ B[\text{true}] = \{(\sigma, \text{true})\} \]
\[ B[\text{false}] = \{(\sigma, \text{false})\} \]
\[ B[a_1 < a_2] = \{(\sigma, \text{true}) \mid (\sigma, n_1) \in A[a_1] \land (\sigma, n_2) \in A[a_2] \land n_1 < n_2\} \cup \{(\sigma, \text{false}) \mid (\sigma, n_1) \in A[a_1] \land (\sigma, n_2) \in A[a_2] \land n_1 \geq n_2\} \]

The denotations for commands are as follows:

\[ C[\text{skip}] = \{(\sigma, \sigma)\} \]
\[ C[x := a] = \{(\sigma, \sigma[x \mapsto n]) \mid (\sigma, n) \in A[a]\} \]
\[ C[c_1; c_2] = \{(\sigma, \sigma') \mid \exists \sigma''. ((\sigma, \sigma'') \in C[c_1] \land (\sigma'', \sigma') \in C[c_2])\} \]

Note that \( C[c_1; c_2] = C[c_2] \circ C[c_1] \), where \( \circ \) is the composition of relations, defined as follows: if \( R_1 \subseteq A \times B \) and \( R_2 \subseteq B \times C \) then \( R_2 \circ R_1 \subseteq A \times C \) is \( R_2 \circ R_1 = \{(a, c) \mid \exists b \in B. (a, b) \in R_1 \land (b, c) \in R_2\} \). If \( C[c_1] \) and \( C[c_2] \) are total functions, then \( \circ \) is function composition.

\[ C[\text{if} \ b \ \text{then} \ c_1 \ \text{else} \ c_2] = \{(\sigma, \sigma') \mid (\sigma, \text{true}) \in B[b] \land (\sigma, \sigma') \in C[c_1]\} \cup \{(\sigma, \sigma') \mid (\sigma, \text{false}) \in B[b] \land (\sigma, \sigma') \in C[c_2]\} \]
\[ C[\text{while} \ b \ \text{do} \ c] = \{(\sigma, \sigma) \mid (\sigma, \text{false}) \in B[b]\} \cup \{(\sigma, \sigma') \mid (\sigma, \text{true}) \in B[b] \land \exists \sigma''. ((\sigma, \sigma'') \in C[c] \land (\sigma'', \sigma') \in C[\text{while} \ b \ \text{do} \ c])\} \]

But now we have a problem: the last “definition” is not really a definition because it expresses \( C[\text{while} \ b \ \text{do} \ c] \) in terms of itself! This is not a definition but a recursive equation. What we want is the solution to this equation.

2 Fixed points

We gave a recursive equation that the function \( C[\text{while} \ b \ \text{do} \ c] \) must satisfy. To understand some of the issues involved, let’s consider a simpler example. Consider the following equation for a function \( f : \mathbb{N} \to \mathbb{N} \).

\[ f(x) = \begin{cases} 0 & \text{if } x = 0 \\ f(x - 1) + 2x - 1 & \text{otherwise} \end{cases} \]

(1)

This is not a definition for \( f \), but rather an equation that we want \( f \) to satisfy. What function, or functions, satisfy this equation for \( f \)? The only solution to this equation is the function \( f(x) = x^2 \).

In general, there may be no solutions for a recursive equation (e.g., there are no functions \( g : \mathbb{N} \to \mathbb{N} \) that satisfy the recursive equation \( g(x) = g(x) + 1 \), or multiple solutions (e.g., find two functions \( g : \mathbb{R} \to \mathbb{R} \) that satisfy \( g(x) = 4 \times g\left(\frac{x}{2}\right) \)).
We can compute solutions to such equations by building successive approximations. Each
approximation is closer and closer to the solution. To solve the recursive equation for \( f \), we start
with the partial function \( f_0 = \emptyset \) (i.e., \( f_0 \) is the empty relation; it is a partial function with the empty
set for it’s domain). We compute successive approximations using the recursive equation.

\[
f_0 = \emptyset
\]

\[
f_1 = \begin{cases} 
  0 & \text{if } x = 0 \\
  f_0(x-1) + 2x - 1 & \text{otherwise}
\end{cases}
= \{(0,0)\}
\]

\[
f_2 = \begin{cases} 
  0 & \text{if } x = 0 \\
  f_1(x-1) + 2x - 1 & \text{otherwise}
\end{cases}
= \{(0,0),(1,1)\}
\]

\[
f_3 = \begin{cases} 
  0 & \text{if } x = 0 \\
  f_2(x-1) + 2x - 1 & \text{otherwise}
\end{cases}
= \{(0,0),(1,1),(2,4)\}
\]

\[ \vdots \]

This sequence of successive approximations \( f_i \) gradually builds the function \( f(x) = x^2 \).

We can model this process of successive approximations using a higher-order function \( F \) that
takes one approximation \( f_k \) and returns the next approximation \( f_{k+1} \):

\[
F : (\mathbb{N} \rightarrow \mathbb{N}) \rightarrow (\mathbb{N} \rightarrow \mathbb{N})
\]

where

\[
(F(f))(x) = \begin{cases} 
  0 & \text{if } x = 0 \\
  f(x-1) + 2x - 1 & \text{otherwise}
\end{cases}
\]

A solution to the recursive equation 1 is a function \( f \) such that \( f = F(f) \). In general, given a
function \( F : A \rightarrow A \), we have that \( a \in A \) is a fixed point of \( F \) if \( F(a) = a \). We also write \( a = \text{fix}(F) \)
to indicate that \( a \) is a fixed point of \( F \).

So the solution to the recursive equation 1 is a fixed-point of the higher-order function \( F \). We
can compute this fixed point iteratively, starting with \( f_0 = \emptyset \) and at each iteration computing
\( f_{k+1} = F(f_k) \). The fixed point is the limit of this process:

\[
f = \text{fix}(F)
= f_0 \cup f_1 \cup f_2 \cup f_3 \cup \ldots
= \emptyset \cup F(\emptyset) \cup F(F(\emptyset)) \cup F(F(F(\emptyset))) \cup \ldots
= \bigcup_{i \geq 0} F^i(\emptyset)
\]