Reduction (or Contextual) Semantics

CPSC 509: Programming Language Principles

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We learned about structural operational small-step semantics, which let us reason about the process of computation when evaluating a value. These semantics capture program execution as small rewrites on bits of a program, captured by a derivation tree that finds a single piece of work and does it. We can make this idea of computation-as-local-rewrites more explicit which can make for concise specifications, and later will be useful for defining the semantics of programming language features that implement complex control operations like exceptions and continuations.

We introduce reduction semantics a.k.a. contextual semantics, which is yet another way to define the \( \rightarrow \) single-step relation.

1 Evaluation Contexts

We already learned about the idea of frames for abstracting the structural rules of a structural operational semantics:

\[
  f \in \text{FRAME}
\]

\[
  f ::= \text{if } \Box \text{ then } t_1 \text{ else } t_2 | \text{succ}(\Box) | \text{pred}(\Box) | \text{zero?}(\Box)
\]

Each frame captures a single expression with a hole in it. Then our \((sf)\) frame rule can repeatedly appeal to frames to decompose a program and find an interesting computation.

Reduction semantics refactor the combination of frames and rules by pushing the combination of frames into the syntax of evaluation contexts, leaving the need for only a single level of rule application to define the single-step relation.

To capture the entire context in which a computation may happen, we define the set \( \text{EC}\text{TXT} \) of evaluation contexts:

\[
  E \in \text{EC}\text{TXT}
\]

\[
  E ::= \Box | E[\text{if } \Box \text{ then } t \text{ else } t] | E[\text{succ}(\Box)] | E[\text{pred}(\Box)] | E[\text{zero?}(\Box)]
\]

The idea here is that we can build up a context of computation by following the small-step structural rules and replacing them with context frames. So for example, \( \Box \) is the empty context. If we place a \( \text{succ}(\Box) \) frame inside its hole, we get a new context; if we place a \( \text{pred}(\Box) \) frame inside of that context’s hole, then we get yet another context. Thus, the evaluation context \( \Box[\text{succ}(\Box)][\text{pred}(\Box)] \) corresponds to the program-with-a-hole \( \text{succ} (\text{pred}(\Box)) \).

Now bear in mind that the notation we use for evaluation contexts is meant to give you an intuition for what things mean. The hole notation \( \Box \) gives you a sense that you could stick something in there to either make a bigger context or a whole program. That’s why we use \( E[\ldots] \) as notation for sticking \( \ldots \) in \( E \)’s hole. However, the use of brackets here is not to be confused with the plug function that we defined for frames. It may be helpful, though to consider a desugared tree-like representation of evaluation contexts, much like our early presentation of the Boolean language, where we had atoms like \text{if} and we drew trees in parenthesized style. Here is a TREE-like presentation of evaluation contexts:

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\[ E ::= \text{hole} \mid \text{in-if}(E, t_1, t_2) \mid \text{in-succ}(E) \mid \text{in-pred}(E) \mid \text{in-zero?}(E) \]

If we strip away the syntactic sugar and look at this structure, a few things become apparent. Notice that there is only one explicit reference to a hole, in the top-level \text{hole} structure, but the tree structures like \text{in-succ} just carry an evaluation context. This is so because it is an implicit property of \text{in-succ} that there is a hole in its argument position. To make this clearer, suppose we also wanted to support evaluation in the consequent position of an \text{if} expression. In the structural operational semantics, that would correspond to adding a rule:

\[
\frac{t_2 \rightarrow t'_2}{\text{if} \ t_1 \ \text{then} \ t_2 \ \text{else} \ t_3 \rightarrow \text{if} \ t_1 \ \text{then} \ t'_2 \ \text{else} \ t_3}
\]

In our sugared evaluation contexts, this corresponds to adding a new case:

\[ E ::= \ldots \mid E[\text{if} \ t_1 \ \text{then} \ \Box \ \text{else} \ t_3] \]

but in our tree-based representation it does as well:

\[ E ::= \ldots \mid \text{in-if-conseq}(E, t_1, t_3) \]

So we tell where the hole is in an \text{if} expression based on which context frame we are introducing: \text{in-if} or \text{in-if-conseq}.

Finally, notice that the construction \text{in-succ}(E) takes as its argument it’s surrounding context. That’s how this corresponds to \(E[\text{succ}(\Box)]\). This is why this form of evaluation context is called \text{inside-out} evaluation contexts because when you have a context \(E\), you can immediately see the inner-most context frame, and as you decompose it, you work your way out to the top of the program\(^1\).

Using our tree-based representation, \(\Box[\text{succ}(\Box)][\text{pred}(\Box)]\) is written \text{in-pred}(\text{in-succ}(\text{hole})).

## 2 Plugging

Now that we have a representation of a program with a hole in it, we need a way to talk about an entire program. Intuitively, if I have a context \(E\), and I plug its hole with a term \(t\), then the result should be an entire program. This is exactly the case, and we capture this by defining a plug function that works just like the one for frames \(\cdot : E\text{TXT} \times \text{TERM} \rightarrow \text{TERM}\) as follows:

\[
\Box[t] = t \\
(E[\Box \text{then} t_1 \text{else} t_2])[t] = E[\text{if} \ t \ \text{then} \ t_1 \ \text{else} \ t_2] \\
(E[\text{succ}(\Box)][t] = E[\text{succ}(t)] \\
(E[\text{pred}(\Box)][t] = E[\text{pred}(t)] \\
(E[\text{zero?}(\Box)][t] = E[\text{zero?}(t)]
\]

Notice that plug is defined by recursion on the structure of evaluation contexts. As a helpful exercise, you should state the principle of recursion for evaluation contexts, and see if you can redefine plug in longhand form.

Note that the plug function \(E[t]\) is technically a different thing from the context constructors like \(E[\text{succ}(\Box)]\). It’s a bit unfortunate that the same notation is used for technically different things, but on the other hand the two are intuitively similar, so this overloading is a bit nice but could be formally misleading.

## 3 Reduction Semantics

We now have all of the machinery needed to re-present the semantics of the Boolean and Arithmetic Language as a reduction semantics. Keep in mind that both reduction semantics and structural operational semantics can be viewed as different ways of describing the meaning of programs. The reduction semantics provides a direct way to compute the result of a program, while the structural operational semantics describes how the program is evaluated step-by-step.

\(^1\)There is also a notion of \text{outside-in} context, but we defer its description for now
semantics are examples of small step semantics. Not only this, both proceed by defining a small-step relation \(\rightarrow\), and then define the evaluator in terms of \(\rightarrow^*\), the reflexive transitive closure of \(\rightarrow\). In fact, the resulting relation \(\rightarrow\) is exactly the same in both cases. So what changed? As usual, what changed was the structure of the definition, which gives you a different way of looking at the same language, and also gives you different principles for reasoning about programs and the language as a whole.

Here are the main pieces of the reduction semantics. We start with the syntax of the language:

\[
\begin{align*}
  t & \in \text{TTERM} \\
  v & \in \text{VALUE} \\
  nv & \in \text{NUM}
\end{align*}
\]

\[
\begin{align*}
  t ::= & \ \text{true} \mid \text{false} \mid \text{if } t \text{ then } t \text{ else } t \\
  & \mid z \mid \text{succ}(t) \mid \text{pred}(t) \mid \text{zero?}(t)
\end{align*}
\]

\[
\begin{align*}
  v ::= & \ \text{true} \mid \text{false} \mid nv
\end{align*}
\]

\[
\begin{align*}
  nv ::= & \ z \mid \text{succ}(nv)
\end{align*}
\]

Then we introduce the syntax of evaluation contexts, which replaces all of the structural rules from the structural operational semantics:

\[
E \in \text{ECTXT}
\]

\[
E ::= \square \mid E[\text{if } \square \text{ then } t_1 \text{ else } t_2] \mid E[\text{succ}(\square)] \mid E[\text{pred}(\square)]E[\text{zero?}(\square)]
\]

Then we introduce the interesting computational rules, which are called notions of reduction (for no great reason as far as I can tell). The notions of reduction form a binary relation \(\rightarrow \subseteq \text{TTERM} \times \text{TTERM}:
\[
\begin{align*}
  &\text{if true then } t_2 \text{ else } t_3 \rightarrow t_2 \\
  &\text{if false then } t_2 \text{ else } t_3 \rightarrow t_3 \\
  &\text{pred}(\text{succ}(nv)) \rightarrow nv \\
  &\text{zero?}(z) \rightarrow \text{true} \\
  &\text{zero?}(\text{succ}(nv)) \rightarrow \text{false}
\end{align*}
\]

The notions of reduction only characterize the interesting steps of computation. We need to combine them with the evaluation contexts if we are to describe computation over arbitrary programs. We now define our single-step relation \(\rightarrow\) in terms of our notions of reduction, our plug function, and our evaluation contexts:

\[
\frac{t_1 \rightarrow t_2}{E[t_1] \rightarrow E[t_2]}
\]

As with frame-style S.O.S., this definition uses the plug function as a sugared side-condition. We can rewrite the above inference rule to better indicate what components of it are side-conditions and what components are part of the rule:

\[
\frac{t_a \rightarrow t_b}{t_a = E[t_1], t_b = E[t_2], \text{ and } t_1 \rightarrow t_2}
\]

In fact, since there are no premises, this is a rather flat inductive definition (to see why I say so, write down the principle of induction for this definition). We could also write it down as in set comprehension notation and add quantifiers to make it a little more precise:

\[
\rightarrow = \{ (t_a, t_b) \subseteq \text{TTERM} \times \text{TTERM} \mid \exists E \in \text{ECTXT}. \exists t_1 \in \text{TTERM}. \exists t_2 \in \text{TTERM}. t_a = E[t_1] \land t_b = E[t_2] \land t_1 \rightarrow t_2 \}.
\]

This definition is equivalent to the rule-based definition above.

To make these concepts clearer, consider the program:

\[
\text{if zero?} (\text{pred} (\text{succ} (z))) \text{ then false else true.}
\]

Under reduction semantics, we can simply underline the term that is subject to the notion of reduction at each step.

\[
\begin{align*}
  &\text{if zero?} (\text{pred} (\text{succ} (z))) \text{ then false else true} \\
  \rightarrow &\text{if zero?} (z) \text{ then false else true} \\
  \rightarrow &\text{if true then false else true} \\
  \rightarrow &\text{false}.
\end{align*}
\]
Under structural operational semantics, each of these steps requires a proof tree. Under reduction semantics, on the other hand, each step requires an evaluation context \( E \), and a notion of reduction \( t_1 \rightsquigarrow t_2 \).

4 Discussion

One nice feature of reduction semantics is that they are very compact: provide a syntax for evaluation contexts, a set of notions of reduction, and you can always assume the definition of \( \rightarrow \). Furthermore, we’ll find that this definition style makes some language features easier to define, or clearer to understand. It’s also the case that this style of definition is more closely related to how you might implement such a language than structural operational semantics.

The downside is that we lose our ability to prove things by induction, since the rules were our source of induction principles (induction over the structure of the context is often not helpful). However, if a reduction semantics is well structured, then we can reverse-engineer a structural operational semantics from it if we need one.

References