Recursive Definitions

• Given a Scott-domain $D$, we can write equations of the form:

$$f \equiv E_f$$

where $E_f$ is an expression constructed from constants in $D$, operations (continuous functions) on $D$, and $f$.

• Example: let $D$ be the domain of Jam values. Then

$$\text{fact} \equiv \text{map } n \text{ to if } n = 0 \text{ then } 1 \text{ else } n \ast \text{fact}(n - 1)$$

is such an equation.

• Such equations are called *recursive definitions*. 
Solutions to Recursion Equations

Given a recursion equation:

\[ f \equiv E_f \]

what is a solution? All of the constants and operations in \( E_f \) are known except \( f \).

A solution is any function \( f \) such that \( f = E_f \).

But there may be more than one solution. We want to select the “best” solution \( f^* \). Note that \( f^* \) is an element of whatever domain \( D^* \) corresponds to the type of \( E_f \). In the most common case, it is \( D \rightarrow D \), but it can be \( D, D \rightarrow D, \ldots, D^k \rightarrow D, \ldots \). The best solution \( f^* \) (which always exists and is unique and computable) is the least solution under the approximation ordering in \( D^* \).
Constructing the Least Solution

How do we know that any solution exists to the equation $f = E_f$?

We will construct the least solution and prove it is a solution!

Since the domain $D^*$ for $f$ is a Scott-Domain, this domain has a least element $\bot_{D^*}$ that approximates every solution to the equation.

Now form the function $F: D^* \to D^*$ defined by

$$F(f) = E_f$$

or equivalently,

$$F = \lambda f. \ E_f$$

Consider the sequence $S$: $\bot_{D^*}, F(\bot_{D^*}), F(F(\bot_{D^*})), \ldots, F^k(\bot_{D^*}), \ldots$

Claim $S$ is an ascending chain (chain for short) in $D^* \to D^*$.

Proof. $\bot_{D^*} \leqslant F(\bot_{D^*})$ by the definition of $\text{Bot}_{D^*}$. If $M \leqslant N$, then $F(M) \leqslant F(N)$ by monotonicity. Hence, $F^k(\bot_{D^*}) \leqslant F^{k+1}(\bot_{D^*})$ for all $k$. Q.E.D.

Claim: $S$ has a least upper bound $f^*$

Proof. Trivial. $S$ is a chain in $D^*$ and hence must have a least upper bound because $D^*$ is a Scott-Domain.
Proving $\mathbf{f^*}$ is a fixed point of $\mathbf{F}$

Must show: $\mathbf{F(f^*) = f^*}$ where $\mathbf{F = \lambda f . E_f}$.

Claim: By definition $\mathbf{f^* = \bigcup F^k (\perp_{D^*})}$. Since $\mathbf{F}$ is continuous

\[
\begin{align*}
\mathbf{F(f^*)} &= \mathbf{F(\bigcup F^k (\perp_{D^*}))} \\
&= \bigcup F^{k+1} (\perp_{D^*}) \quad \text{(by continuity)} \\
&= \bigcup F^k (\perp_{D^*}) \quad \text{(since $\perp_{D^*} \leq F(\perp_{D^*})$)} \\
&= f^* \\
\end{align*}
\]

Q.E.D.

Note: all of the steps in the preceding proof are trivial except for the step justified by continuity.
Examples

Look at factorial in detail using DrRacket stepper.
How Can We Compute $f^*$ Given $F$?

Need to construct $F^\infty(\bot)$ from $F$. Let $Y(F) = f^* = F^\infty(\bot)$.

Can we write code for $Y$?

Idea: use syntactic trick in $\Omega$ to build a potentially infinite stack of $F$s.

- Preliminary attempt:
  
  $$(\lambda x. F(x 
  x)) (\lambda x. F(x 
  x))$$

- Reduces to (in one step):
  
  $F ((\lambda x. F(x 
  x)) (\lambda x. F(x 
  x)))$

- Reduces to (in $k$ steps):
  
  $F^k ((\lambda x. F(x 
  x)) (\lambda x. F(x 
  x)))$
What Is the Code for \( \mathbf{Y} \)?

\[
\lambda F. \ (\lambda x. \ F(x \ x)) \ (\lambda x. \ F(x \ x))
\]

• Does this work for Scheme (or Java with an appropriate encoding of functions as anonymous inner classes)? No!

• Why not? What about divergence? Assume \( G \) is a \( \lambda \)-expression defining a functional like \( \text{FACT} \)

\[
(\lambda F. \ (\lambda x. \ F(x \ x)) \ (\lambda x. \ F(x \ x))) \ G
= \ G((\lambda x. \ G(x \ x)) \ (\lambda x. \ G(x \ x)))
= \ \ldots \ (\text{diverging})
\]
What If We Use Call-by-name?

By assumption $G$ must have the form $\lambda f. \lambda n . M$

$$(\lambda F. (\lambda x. F(x x)) (\lambda x. F(x x))) G$$

$$= G ((\lambda x. G(x x)) (\lambda x. G(x x)))$$

$$= (\lambda f. \lambda n . M) ((\lambda x. G(x x)) (\lambda x. G(x x)))$$

$$= \lambda n . M[x:=((\lambda x. G(x x)) (\lambda x. G(x x)))]$$

If the evaluation $M$ of does not require evaluating an occurrence of $f$, then $x$ is not evaluated. Otherwise, the binding of $x$ is unwound only as many times as required to get to the base case in the definition $f = \lambda n . M$.

Exercise: how can we workaround this problem to create a version of the $Y$ operator that works for call-by-value Scheme and Jam? Hint: if $M$ is a divergent term denoting a unary function $\lambda x. Mx$ is an “equivalent” term that is not divergent! (As a concrete example, assume that $M$ is the term $\Omega$.)