Proof Techniques for Operational Semantics
Small-Step Contextual Semantics

- In small-step contextual semantics, derivations are not tree-structured.
- A contextual semantics derivation is a sequence (or list) of atomic rewrites:

  \[ <x+(7-3), \sigma> \rightarrow <x+(4), \sigma> \rightarrow <5+4, \sigma> \rightarrow <9, \sigma> \]

  \[ \sigma(x)=5 \]

If \( <r, \sigma> \rightarrow <e, \sigma'> \) then \( <H[r], \sigma> \rightarrow <H[e], \sigma'> \)

\( r = \text{redex} \)
\( H = \text{context (has hole)} \)
Context Decomposition

• Decomposition theorem:
  If c is not “skip” then there exist unique H and r such that c is H[r]
  - “Exist” means progress
  - “Unique” means determinism
Short-Circuit Evaluation

• What if we want to express short-circuit evaluation of \( \land \) ?
  - Define the following contexts, redexes and local reduction rules

\[
H ::= \ldots \mid H \land b_2
\]

\[
r ::= \ldots \mid \text{true} \land b \mid \text{false} \land b
\]

\[
<\text{true} \land b, \sigma> \rightarrow <b, \sigma>
\]

\[
<\text{false} \land b, \sigma> \rightarrow <\text{false}, \sigma>
\]

- the local reduction kicks in before \( b_2 \) is evaluated
Contextual Semantics Summary

- Can view • as representing the program counter
- Contextual semantics is inefficient to implement directly

- The major advantage of contextual semantics: it allows a mix of local and global reduction rules
  - For IMP we have only local reduction rules: only the redex is reduced
  - Sometimes it is useful to work on the context too
  - We’ll do that when we study memory allocation, etc.
Cunning Plan for Proof Techniques

- Why Bother?
- Mathematical Induction
- Well-Founded Induction
- Structural Induction
  - "Induction On The Structure Of The Derivation"
One-Slide Summary

• **Mathematical Induction** is a proof technique: If you can prove $P(0)$ and you can prove that $P(n)$ implies $P(n+1)$, then you can conclude that for all natural numbers $n$, $P(n)$ holds.

• Induction works because the natural numbers are well-founded: there are no infinite descending chains $n > n-1 > n-2 > \ldots > \ldots$.

• **Structural induction** is induction on a formal structure, like an AST. The base cases use the leaves, the inductive steps use the inner nodes.

• **Induction on a derivation** is structural induction applied to a derivation $D$ (e.g., $D::<c, \sigma> \downarrow \sigma'$).
Why Bother?

• I am loathe to teach you anything that I think is a waste of your time.
• Thus I must convince you that inductive opsem proof techniques are useful.
  - Recall class goals: understand PL research techniques and apply them to your research
• This motivation should also highlight where you might use such techniques in your own research.
Never Underestimate

“Any counter-example posed by the Reviewers against this proof would be a useless gesture, no matter what technical data they have obtained. Structural Induction is now the ultimate proof technique in the universe. I suggest we use it.” --- Admiral Motti, A New Hope
Classic Example (Schema)

• “A well-typed program cannot go wrong.”
  - Robin Milner

• When you design a new type system, you must show that it is safe (= that the type system is sound with respect to the operational semantics).

• A *Syntactic Approach to Type Soundness*. Andrew K. Wright, Matthias Felleisen, 1992.
  - Type preservation: “if you have a well-typed program and apply an opsem rule, the result is well-typed.”
  - Progress: “a well-typed program will never get stuck in a state with no applicable opsem rules”

• Done for real languages: SML/NJ, SPARK ADA, Java
  - PL/I, plus basically every toy PL research language ever.
Classic Examples

- **CCured Project (Berkeley)**
  - A program that is instrumented with CCured run-time checks (= “adheres to the CCured type system”) will not segfault (= “the x86 opsem rules will never get stuck”).

- **Vault Language (Microsoft Research)**
  - A well-typed Vault program does not leak any tracked resources and invokes tracked APIs correctly (e.g., handles IRQL correctly in asynchronous Windows device drivers, cf. Capability Calculus)

- **RC - Reference-Counted Regions For C (Intel Research)**
  - A well-typed RC program gains the speed and convenience of region-based memory management but need never worry about freeing a region too early (run-time checks).

- **Typed Assembly Language (Cornell)**
  - Reasonable C programs (e.g., device drivers) can be translated to TALx86. Well-typed TALx86 programs are type- and memory-safe.

- **Secure Information Flow (Many, e.g., Volpano et al. ‘96)**
  - Lattice model of secure flow analysis is phrased as a type system, so type soundness = noninterference.
Recent Examples

- “We prove soundness (Theorem 6.8) by mutual induction on the derivations of …”
  - An Operational and Axiomatic Semantics for Non-determinism and Sequence Points in C, POPL 2014
- “The proof goes by induction on the structure of p.”
  - NetKAT: Semantic Foundations of Networks, POPL 2014
- “The operational semantics is given as a big-step relation, on which our compiler correctness proofs can all proceed by induction …”
  - CakeML: A Verified Implementation of ML, POPL 2014
- Method: Chose 4 papers from POPL 2014, 3 of them use structural induction.
Decade-Old Examples

- “The proof proceeds by rule induction over the target term producing translation rules.”
  - Chakravarty et al. ’05

- “Type preservation can be proved by standard induction on the derivation of the evaluation relation.”
  - Hosoya et al. ’05

- “Proof: By induction on the derivation of $N \downarrow W$.”
  - Sumi and Pierce ’05

- Method: chose four POPL 2005 papers at random, the three above mentioned structural induction.
  (emphasis mine)
Induction

• **Most important technique** for studying the formal semantics of prog languages
  - If you want to perform or understand PL research, **you must grok this**!

• Mathematical Induction (simple)
• Well-Founded Induction (general)
• Structural Induction (widely used in PL)
Mathematical Induction

- **Goal:** prove $\forall n \in \mathbb{N}. P(n)$

- **Base Case:** prove $P(0)$

- **Inductive Step:**
  - Prove $\forall n > 0. P(n) \Rightarrow P(n+1)$
  - “Pick arbitrary $n$, assume $P(n)$, prove $P(n+1)$”

- Why does induction work?
Why Does It Work?

- There are no infinite descending chains of natural numbers.
- For any $n$, $P(n)$ can be obtained by starting from the base case and applying $n$ instances of the inductive step.
Well-Founded Induction

• A relation $\leq \subseteq A \times A$ is well-founded if there are no infinite descending chains in $A$
  - Example: $<_1 = \{ (x, x +1) | x \in \mathbb{N} \}$
    • aka the predecessor relation
  - Example: $< = \{ (x, y) | x, y \in \mathbb{N} \text{ and } x < y \}$

• Well-founded induction:
  - To prove $\forall x \in A. \ P(x)$ it is enough to prove $\forall x \in A. \ [\forall y < x \Rightarrow P(y)] \Rightarrow P(x)$

• If $\leq$ is $<_1$ then we obtain mathematical induction as a special case
Structural Induction

- Recall $e ::= n \mid e_1 + e_2 \mid e_1 \ast e_2 \mid x$

- Define $\preceq \subseteq A_{exp} \times A_{exp}$ such that

  $e_1 \preceq e_1 + e_2 \quad e_2 \preceq e_1 + e_2$

  $e_1 \preceq e_1 \ast e_2 \quad e_2 \preceq e_1 \ast e_2$

  - no other elements of $A_{exp} \times A_{exp}$ are $\preceq$-related

- **To prove** $\forall e \in A_{exp}. P(e)$

  - $\vdash \forall n \in \mathbb{Z}. P(n)$
  
  - $\vdash \forall x \in L. P(x)$
  
  - $\vdash \forall e_1, e_2 \in A_{exp}. P(e_1) \land P(e_2) \Rightarrow P(e_1 + e_2)$
  
  - $\vdash \forall e_1, e_2 \in A_{exp}. P(e_1) \land P(e_2) \Rightarrow P(e_1 \ast e_2)$
Notes on Structural Induction

• Called *structural induction* because the proof is guided by the *structure* of the expression

• One proof case per form of expression
  - Atomic expressions (with no subexpressions) are all *base cases*
  - Composite expressions are the *inductive case*

• This is the *most useful form of induction* in the study of PL
Example of Induction on Structure of Expressions

- Let
  - $L(e)$ be the # of literals and variable occurrences in $e$
  - $O(e)$ be the # of operators in $e$

- Prove that $\forall e \in Aexp. \ L(e) = O(e) + 1$

- Proof: by induction on the structure of $e$
  - Case $e = n$. $L(e) = 1$ and $O(e) = 0$
  - Case $e = x$. $L(e) = 1$ and $O(e) = 0$
  - Case $e = e_1 + e_2$.
    - $L(e) = L(e_1) + L(e_2)$ and $O(e) = O(e_1) + O(e_2) + 1$
    - By induction hypothesis $L(e_1) = O(e_1) + 1$ and $L(e_2) = O(e_2) + 1$
    - Thus $L(e) = O(e_1) + O(e_2) + 2 = O(e) + 1$
  - Case $e = e_1 * e_2$. Same as the case for $+$
Other Proofs by Structural Induction on Expressions

- Most proofs for Aexp sublanguage of IMP
- Small-step and natural semantics obtain equivalent results:
  \[ \forall e \in \text{Exp. } \forall n \in \mathbb{N}. \quad e \rightarrow^* n \iff e \downarrow n \]

- Structural induction on expressions works here because all of the semantics are syntax directed
Stating The Obvious (With a Sense of Discovery)

• You are given a concrete state $\sigma$.
• You have $\vdash <x + 1, \sigma> \downarrow 5$
• You also have $\vdash <x + 1, \sigma> \downarrow 88$
• Is this possible?
Why That Is Not Possible

- Prove that IMP is **deterministic**
  \[
  \forall e \in \text{Aexp. } \forall \sigma \in \Sigma. \forall n, n' \in \mathbb{N}. \ <e, \sigma> \downarrow n \land <e, \sigma> \downarrow n' \Rightarrow n = n'
  \]
  \[
  \forall b \in \text{Bexp. } \forall \sigma \in \Sigma. \forall t, t' \in \mathbb{B}. \ <b, \sigma> \downarrow t \land <b, \sigma> \downarrow t' \Rightarrow t = t'
  \]
  \[
  \forall c \in \text{Comm. } \forall \sigma, \sigma', \sigma'' \in \Sigma. \ <c, \sigma> \downarrow \sigma' \land <c, \sigma> \downarrow \sigma'' \Rightarrow \sigma' = \sigma''
  \]

- No immediate way to use *mathematical* induction

- For commands we cannot use *induction on the structure of the command*
  - while's evaluation does *not* depend only on the evaluation of its strict subexpressions
    \[
    \begin{align*}
    <b, \sigma> & \downarrow \text{true} \quad <c, \sigma> \downarrow \sigma' \quad \text{<while b do c, } \sigma'> \downarrow \sigma'' \\
    \text{<while b do c, } \sigma & \downarrow \sigma''
    \end{align*}
    \]
Q: Movies (292 / 842)

• From the 1981 movie *Raiders of the Lost Ark*, give either the protagonist's phobia xor the composer of the musical score.
Computer Science

- This Dutch Turing-award winner is famous for the semaphore, “THE” operating system, the Banker's algorithm, and a shortest path algorithm. He favored structured programming, as laid out in the 1968 article *Go To Statement Considered Harmful*. He was a strong proponent of formal verification and correctness by construction. He also penned *On The Cruelty of Really Teaching Computer Science*, which argues that CS is a branch of math and relates provability to correctness.
Recall Opsem

- **Operational semantics** assigns meanings to programs by listing **rules of inference** that allow you to prove **judgments** by making derivations.

- A **derivation** is a tree-structured object made up of valid instances of inference rules.
We Need Something New

• Some more powerful form of induction ...
• With all the bells and whistles!
Induction on the Structure of Derivations

- Key idea: The hypothesis does not just assume a $c \in \text{Comm}$ but the existence of a derivation of $\langle c, \sigma \rangle \Downarrow \sigma'$
- Derivation trees are also defined inductively, just like expression trees
- A derivation is built of subderivations:
  - $\langle x, \sigma_{i+1} \rangle \Downarrow 5 - i$, $5 - i \leq 5$
  - $\langle x + 1, \sigma_{i+1} \rangle \Downarrow 6 - i$
  - $\langle \text{while } x \leq 5 \text{ do } x := x + 1, \sigma_{i+1} \rangle \Downarrow \sigma_0$
- Adapt the structural induction principle to work on the structure of derivations
Induction on Derivations

- To prove that for all derivations $D$ of a judgment, property $P$ holds
  - For each derivation rule of the form
    $$
    \frac{H_1 \ldots H_n}{C}
    $$
    - Assume $P$ holds for derivations of $H_i$ ($i = 1..n$)
    - Prove the property holds for the derivation obtained from the derivations of $H_i$ using the given rule
New Notation

- Write $D :: \text{Judgment}$ to mean “$D$ is the derivation that proves Judgment”

- Example:

$$D :: <x+1, \sigma> \downarrow 2$$
Induction on Derivations (2)

• Prove that evaluation of commands is deterministic:
  \[ \langle c, \sigma \rangle \Downarrow \sigma' \Rightarrow \forall \sigma'' \in \Sigma. \langle c, \sigma \rangle \Downarrow \sigma'' \Rightarrow \sigma' = \sigma'' \]

• Pick arbitrary \( c, \sigma, \sigma' \) and \( D :: \langle c, \sigma \rangle \Downarrow \sigma' \)

• To prove: \( \forall \sigma'' \in \Sigma. \langle c, \sigma \rangle \Downarrow \sigma'' \Rightarrow \sigma' = \sigma'' \)
  - Proof: by induction on the structure of the derivation \( D \)

• Case: last rule used in \( D \) was the one for skip
  \[
  D :: \quad \underline{\quad} \\
  \langle \text{skip}, \sigma \rangle \Downarrow \sigma
  \]
  - This means that \( c = \text{skip} \), and \( \sigma' = \sigma \)
  - By inversion \( \langle c, \sigma \rangle \Downarrow \sigma'' \) uses the rule for skip
  - Thus \( \sigma'' = \sigma \)
  - This is a base case in the induction
Induction on Derivations (3)

- Case: the last rule used in D was the one for sequencing

\[
\text{D} :: \quad \frac{D_1 :: <c_1, \sigma> \downarrow \sigma_1 \quad D_2 :: <c_2, \sigma_1> \downarrow \sigma'}{<c_1; c_2, \sigma> \downarrow \sigma'}
\]

- Pick arbitrary \( \sigma'' \) such that \( D'' :: <c_1; c_2, \sigma> \downarrow \sigma'' \).
  - by inversion \( D'' \) uses the rule for sequencing
  - and has subderivations \( D''_1 :: <c_1, \sigma> \downarrow \sigma''_1 \) and \( D''_2 :: <c_2, \sigma''_1> \downarrow \sigma'' \)

- By induction hypothesis on \( D_1 \) (with \( D''_1 \)): \( \sigma_1 = \sigma''_1 \)
  - Now \( D''_2 :: <c_2, \sigma_1> \downarrow \sigma'' \)
- By induction hypothesis on \( D_2 \) (with \( D''_2 \)): \( \sigma'' = \sigma' \)
- This is a simple inductive case
Induction on Derivations (4)

- Case: the last rule used in $D$ was \texttt{while true}

\[
\begin{align*}
D &::: \begin{array}{ll}
D_1 &: <b, \sigma> \downarrow \text{true} \\
D_2 &: <c, \sigma> \downarrow \sigma_1 \\
D_3 &: \text{<while b do c, } \sigma_1 \downarrow \sigma' \\
\end{array} \\
&\quad \begin{array}{ll}
<\text{while b do c, } \sigma> \downarrow \sigma' \\
\end{array}
\end{align*}
\]

- Pick arbitrary $\sigma''$ s.t. $D''::<\text{while b do c, } \sigma> \downarrow \sigma''$
  - by inversion and determinism of boolean expressions, $D''$ also uses the rule for \texttt{while true}
  - and has subderivations $D''_2 :: <c, \sigma> \downarrow \sigma''_1$ and $D''_3 :: <W, \sigma''_1> \downarrow \sigma''$

- By induction hypothesis on $D_2$ (with $D''_2$): $\sigma_1 = \sigma''_1$
  - Now $D''_3 :: <\text{while b do c, } \sigma_1> \downarrow \sigma''$

- By induction hypothesis on $D_3$ (with $D''_3$): $\sigma'' = \sigma'$
What Do You, The Viewers At Home, Think?

• Let’s do if true together!
• Case: the last rule in D was if true

\[
D :: \begin{align*}
D_1 :: & \langle b, \sigma \rangle \downarrow \text{true} \\
D_2 :: & \langle c1, \sigma \rangle \downarrow \sigma_1 \\
& \langle \text{if } b \text{ do } c1 \text{ else } c2, \sigma \rangle \downarrow \sigma_1
\end{align*}
\]

• Try to do this on a piece of paper. In a few minutes I’ll have some lucky winners come on down.
Induction on Derivations (5)

• Case: the last rule in D was \textbf{if true}

\[D :: \begin{array}{c}
D_1 :: \langle b, \sigma \rangle \Downarrow \text{true} \\
D_2 :: \langle c_1, \sigma \rangle \Downarrow \sigma'
\end{array}
\]

\[\langle \text{if } b \text{ do } c_1 \text{ else } c_2, \sigma \rangle \Downarrow \sigma'
\]

• Pick arbitrary \( \sigma'' \) such that

\[D'' :: \langle \text{if } b \text{ do } c_1 \text{ else } c_2, \sigma \rangle \Downarrow \sigma''
\]

- By inversion and determinism, \( D'' \) also uses \textbf{if true}
- And has subderivations \( D''_1 :: \langle b, \sigma \rangle \Downarrow \text{true} \) and \( D''_2 :: \langle c_1, \sigma \rangle \Downarrow \sigma'' \)

• By induction hypothesis on \( D_2 \) (with \( D''_2 \)): \( \sigma' = \sigma'' \)
Induction on Derivations

Summary

• If you must prove $\forall x \in A. \ P(x) \Rightarrow Q(x)$
  - with A inductively defined and P(x) rule-defined
  - we pick arbitrary $x \in A$ and $D :: P(x)$
  - we could do induction on both facts
    • $x \in A$ leads to induction on the structure of x
    • $D :: P(x)$ leads to induction on the structure of D
  - Generally, the induction on the structure of the derivation is more powerful and a safer bet

• Sometimes there are many choices for induction
  - choosing the right one is a trial-and-error process
  - a bit of practice can help a lot
Equivalence

• Two expressions (commands) are equivalent if they yield the same result from all states

\[ e_1 \approx e_2 \iff \forall \sigma \in \Sigma. \forall n \in \mathbb{N}. \]

\[ <e_1, \sigma> \downarrow n \iff <e_2, \sigma> \downarrow n \]

and for commands

\[ c_1 \approx c_2 \iff \forall \sigma, \sigma' \in \Sigma. \]

\[ <c_1, \sigma> \downarrow \sigma' \iff <c_2, \sigma> \downarrow \sigma' \]
Notes on Equivalence

- Equivalence is like logical validity
  - It must hold in all states (= all valuations)
  - \( 2 \approx 1 + 1 \) is like “\( 2 = 1 + 1 \) is valid”
  - \( 2 \approx 1 + x \) might or might not hold.
    - So, 2 is not equivalent to \( 1 + x \)

- Equivalence (for IMP) is **undecidable**
  - If it were decidable we could solve the halting problem for IMP. *How?*

- Equivalence justifies code transformations
  - compiler optimizations
  - code instrumentation
  - abstract modeling

- **Semantics** is the basis for proving equivalence
Equivalence Examples

• skip; c \approx c
• while b do c \approx
  if b then c; while b do c else skip
• If e_1 \approx e_2 then x := e_1 \approx x := e_2
• while true do skip \approx while true do x := x + 1
• Let c be
  while x \neq y do
    if x \geq y then x := x - y else y := y - x
then
(x := 221; y := 527; c) \approx (x := 17; y := 17)
Potential Equivalence

• \((x := e_1; x := e_2) \approx x := e_2\)

• Is this a valid equivalence?
Not An Equivalence

- \((x := e_1; x := e_2) \sim x := e_2\)
- lie. Chigau yo. Dame desu!
- Not a valid equivalence for all \(e_1, e_2\).
- Consider:
  - \((x := x+1; x := x+2) \sim x := x+2\)
- But for \(n_1, n_2\) it’s fine:
  - \((x := n_1; x := n_2) \approx x := n_2\)
Proving An Equivalence

• Prove that "\texttt{skip; c} \equiv c" for all c
• Assume that D :: \langle\texttt{skip; c, }\sigma\rangle \Downarrow \sigma'
• By inversion (twice) we have that

\[
\begin{array}{c}
\text{D} :: \langle \text{skip, } \sigma \rangle \Downarrow \sigma \\
\hline
\text{D}_1 :: \langle \text{c, } \sigma \rangle \Downarrow \sigma'
\end{array}
\]

• Thus, we have \texttt{D}_1 :: \langle c, \sigma \rangle \Downarrow \sigma'
• The other direction is similar
Proving An Inequivalence

• Prove that $x := y \not\sim x := z$ when $y \neq z$

• It suffices to exhibit a $\sigma$ in which the two commands yield different results

• Let $\sigma(y) = 0$ and $\sigma(z) = 1$

• Then

  $<x := y, \sigma> \downarrow \sigma[x := 0]$  
  $<x := z, \sigma> \downarrow \sigma[x := 1]$
Summary of Operational Semantics

- **Precise specification of dynamic semantics**
  - order of evaluation (or that it doesn’t matter)
  - error conditions (sometimes implicitly, by rule applicability; “no applicable rule” = “get stuck”)

- **Simple and abstract** (vs. implementations)
  - no low-level details such as stack and memory management, data layout, etc.

- **Often not compositional** (see while)

- **Basis for many proofs about a language**
  - Especially when combined with type systems!

- **Basis for much reasoning about programs**

- **Point of reference for other semantics**
Homework

• Don't Neglect Your Homework
• Read DPLL(T) and Simplex