Characterising Renaming within OCaml's Module System

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PLAS Seminar
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  - usual engineering problems
    - multi-file programs
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    - build systems …
  - but also due to powerful module system
    - functors
    - module types
    - aliases and constraints …
- Need a formal mechanism for reasoning about renaming
  - Abstract denotational semantics

Example 1: Module Includes and Aliases

```
module A = struct
  let foo = 1
  let bar = 2
end

module B = struct
  include A
  let baz = 3
end

module C = (A : sig val foo : int end)

print_int (A.foo + B.foo + C.foo)
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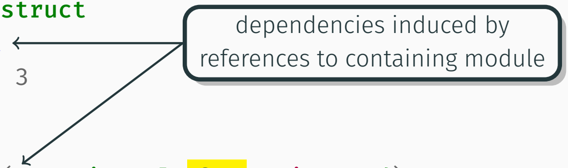

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module C = (struct include A let foo = foo end
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Example 2: Functors

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module type Stringable =
  sig type t val to_string : t -> string end
module Pair (X : Stringable) (Y : Stringable) = struct
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Some Observations

- Basic renamings rely on binding resolution information
- Program structure induces dependencies between basic renamings
- Disparate parts of a program can together make up a single logical meta-level entity

A Formal Theory of Renaming: Roadmap

1. Programs as ASTs and renamings as operations on them
    - AST ‘locations’ allow name-independent representations
2. Define a semantic structure that separately captures:
    - Binding resolution information
    - Meta-level program relationships relevant to renaming
    - Information about concrete names
3. Map programs onto these semantic structures
    - formal properties at the ‘right level of abstraction’
    - methods for constructing/checking renamings

Renamings as Operations on ASTs

$$\text{AST} \quad \sigma \quad : \quad \mathcal{L}oc \to \mathcal{S}yn$$

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A renaming $\sigma \twoheadrightarrow \sigma'$ is a pair of ASTs σ and σ' such that

1. $\text{dom}(\sigma) = \text{dom}(\sigma')$
2. $\sigma(\ell) \in \mathcal{V} \Leftrightarrow \sigma'(\ell) \in \mathcal{V}$
3. $\sigma(\ell) \notin \mathcal{V} \Rightarrow \sigma(\ell) = \sigma'(\ell)$

($\mathcal{V} \subseteq \mathcal{S}yn$ is the set of value identifiers)

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We define the footprint of a renaming $\sigma \twoheadrightarrow \sigma'$

$$\text{foot}(\sigma, \sigma') = \{\ell \mid \ell \in \text{dom}(\sigma) \wedge \sigma(\ell) \neq \sigma'(\ell)\}$$

Two Important Questions

1. When is a renaming $\sigma \twoheadrightarrow \sigma'$ valid?

2. For a given AST σ and $\ell \in \text{decl}(\sigma)$, find σ' such that
   - $\sigma \twoheadrightarrow \sigma'$ is valid
   - $\text{foot}(\sigma, \sigma')$ is minimal and contains ℓ

An Abstract Semantic Structure

$$\Sigma \quad = \quad (\rightarrowtail, \mathbb{E}, \rho)$$

- $\rightarrowtail : \mathcal{L}oc \rightharpoonup \mathcal{L}oc$ is a binding resolution function
- $\mathbb{E} : \mathcal{L}oc \times \mathcal{L}oc$ is a value extension relation
- $\rho : \mathcal{L}oc \rightharpoonup \mathcal{I}$ is a syntactic reification function mapping locations to identifiers

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$[\![\sigma]\!]_{\langle \Gamma, \Sigma \rangle}$ returns the semantics Σ' of the AST σ

$[\![\cdot]\!]$ parameterized by the 'context' semantics $\langle \Gamma, \Sigma \rangle$

The environment Γ gives meaning to identifiers 'in scope'

Interpreting Programs: Binding Resolution

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Semantic Equivalence

We define an ‘up-to-renaming’ equivalence

- $(\rightarrowtail_1, \mathbb{E}_1, \rho_1) \sim (\rightarrowtail_2, \mathbb{E}_2, \rho_2)$ iff
  - $\rightarrowtail_1 = \rightarrowtail_2$
  - $\mathbb{E}_1 = \mathbb{E}_2$
  - $\mathrm{dom}(\rho_1) = \mathrm{dom}(\rho_2)$
  - $\rho_1(\ell) \in \mathcal{V} \Leftrightarrow \rho_2(\ell) \in \mathcal{V}$
  - $\rho_1(\ell) \notin \mathcal{V} \Rightarrow \rho_1(\ell) = \rho_2(\ell)$

- $\Gamma \sim \Gamma'$ iff
  - $(\exists v\ \Gamma(v) = \ell) \Leftrightarrow (\exists v\ \Gamma'(v) = \ell)$
  - $\Gamma(x) = \Gamma'(x)$ (*x* is a module or module type identifier)

Distinguishing Valid Renamings

A valid renaming is one that preserve the equivalence:

- $\sigma \twoheadrightarrow \sigma'$ valid w.r.t. $\langle \Sigma, \Gamma \rangle$ when $\exists\, \Sigma' \sim \Sigma, \Gamma' \sim \Gamma$ such that $[\![\sigma]\!]_{\langle \Sigma, \Gamma \rangle} \sim [\![\sigma']\!]_{\langle \Sigma', \Gamma' \rangle}$

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This does indeed induce an equivalence relation on programs

Theorem (1) $P \twoheadrightarrow P$ is valid (when $[\![P]\!]$ defined)
(2) if $P \twoheadrightarrow P'$ is valid then so is $P' \twoheadrightarrow P$
(3) if $P \twoheadrightarrow P'$ and $P' \twoheadrightarrow P''$ are valid then so is $P \twoheadrightarrow P''$

Constructing Valid Renamings

$\ell \in \mathrm{dom}(\sigma)$ is a declaration of σ when it is a value identifier (i.e. $\sigma(\ell) \in \mathcal{V}$) and there is $\ell' \in \mathrm{dom}(\sigma)$ such that

$\sigma(\ell') =$ `val` v_ℓ `: …` $\qquad$ $\sigma(\ell') =$ `let` v_ℓ `= … in …`

$\sigma(\ell') =$ `let` v_ℓ `= …` $\qquad$ $\sigma(\ell') =$ `fun` v_ℓ `-> …`

Theorem Let $[\![P]\!] = (\rightarrowtail, \mathbb{E}, \rho)$, ℓ be a declaration in P and v a fresh value identifier, then $P \twoheadrightarrow P'$ is a valid renaming, where $P' = P[\ell' \mapsto v \mid \ell' \in [\ell]_{\mathbb{E}} \vee \exists \ell'' \in [\ell]_{\mathbb{E}}.\, \ell' \rightarrowtail \ell'']$

($[\ell]_{\mathbb{E}}$ denotes the $\mathbb{E}$-equivalence class containing ℓ)

Characterising Valid Renamings

We define the dependencies of a renaming $\sigma \twoheadrightarrow \sigma'$ by:

$$\mathrm{deps}(\sigma, \sigma') = \{\ell \mid \ell \in \mathrm{foot}(\sigma, \sigma') \text{ and } \ell \text{ a declaration of } \sigma\}$$

Theorem If $P \twoheadrightarrow P'$ is valid, with $[\![P]\!] = (\rightarrowtail, \mathbb{E}, \rho)$, and let $L = \{\ell \mid \ell \in \mathrm{deps}(P, P') \vee \exists \ell' \in \mathrm{deps}(P, P').\, \ell \rightarrowtail \ell'\}$; then

1. $L \subseteq \mathrm{foot}(P, P')$
2. $\ell \rightarrowtail \bot$ for all $\ell \in \mathrm{foot}(P, P') \setminus L$

Theorem If $P \twoheadrightarrow P'$ is valid, with $[\![P]\!] = (\rightarrowtail, \mathbb{E}, \rho)$, then $\mathrm{deps}(P, P')$ has a partitioning that is a subset of $\mathcal{L}oc_{/\mathbb{E}}$

Adequacy of the Semantics

We define a denotational semantics $(\!|\cdot|\!)$ of the operational meaning of programs

- Extends the model defined by Leroy (POPL '95)
- But module types contribute to the meaning of programs

Theorem If $P \twoheadrightarrow P'$ is a valid renaming, then $(\!|P|\!) = (\!|P'|\!)$

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We do not have a completeness result since valid renamings must preserve shadowing

Rotor: A Prototype Renaming Tool

- Developed in OCaml itself
    - Allows reuse of the compiler infrastructure
- Approximates the approach discussed
    - Only intra-file binding information provided by compiler
    - Inter-file binding information remains as logical paths
- Tested on 2 large codebases
    - Jane Street public libraries (~900 files, ~3000 test cases)
    - OCaml compiler (~500 files, ~2650 test cases)

Experimental Results: Jane Street Codebase

Rebuild Succeeded (37%)

	Files	Hunks	Deps	Avg. Hunks/File
Max	50	128	1127	5.7
Mean	5.0	7.5	24.0	1.3
Mode	3	3	19	1.0

Rebuild Failed (63%)

	Files	Hunks	Deps	Avg. Hunks/File
Max	66	305	3365	8
Mean	7.0	12.0	133.4	1.4
Mode	3	3	1	1.0

Experimental Results: OCaml Compiler Codebase

Rebuild Succeeded (68%)

	Files	Hunks	Deps	Avg. Hunks/File
Max	19	59	35	15.0
Mean	3.8	5.9	1.6	1.5
Mode	3	3	1	1.0

Rebuild Failed (32%)

	Files	Hunks	Deps	Avg. Hunks/File
Max	83	544	56	14.2
Mean	10.2	23.3	10.8	1.7
Mode	4	4	1	1.0

Conclusions

- We have developed a framework for formally describing and reasoning about renaming in OCaml
- Based on a compositional, denotational semantics for a core calculus
- Enables precise statements describing relevant concepts at the right abstraction level
- Implemented a prototype renaming tool based on this approach