Practical performance enhancements to the evaluation model of the Hazel programming environment

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Overview I

Project context

Implementation-based Mostly practically-driven

Functional programming Context for PL theory

Hazel live programming environment An experimental editor with typed holes aimed at solving the "gap problem," developed at UM

Overview II

Project scope

Evaluation with environments Lazy variable lookup for performance

Hole instances to hole closures Redefining hole instances for performance

Implementing fill-and-resume (FAR) Efficiently resume evaluation

Project evaluation

Empirical evaluation Measure performance gain of motivating cases

Informal metatheory State metatheorems and provide proof sketches

Table of Contents

A programming language is a specification

Syntax is the grammar of a valid program

Semantics describes the behavior of a syntactically valid program

$$\tau ::= \tau \to \tau \mid b \mid (\!|\,|\!)$$
$$e ::= c \mid x \mid \lambda x : \tau . e \mid e\ e \mid e : \tau \mid (\!|\,|\!) \mid (\!|e|\!)$$

Figure: Hazelnut grammar

Static and dynamic semantics

Statics Edit actions, type-checking, elaboration ("compile-time")

Dynamics Evaluation ("run-time")

$$\frac{e_1 \Downarrow \lambda x.e_1' \qquad e_2 \Downarrow e_2' \qquad [e_2'/x]e_1' = e}{e_1\ e_2 \Downarrow e}\ \text{EAp}$$

Figure: Evaluation rule for function application using a big-step semantics

A brief primer on the λ-calculus

Untyped λ-calculus Simple universal model of computation by Church

Simply-typed λ-calculus Extension of the ULC with static type-checking

Gradually-typed λ-calculus Optionally-typed, with "pay-as-you-go" benefits of static typing

$$
\begin{aligned}
e ::= {} & x \\
\mid {} & \lambda x.e \\
\mid {} & e\ e
\end{aligned}
$$

(a) Grammar

$$\frac{}{\lambda x.e \Downarrow \lambda x.e}\ \Lambda\text{-ELam}$$

$$\frac{e_1 \Downarrow \lambda x.e_1' \qquad [e_2/x]e_1' \Downarrow e}{e_1\ e_2 \Downarrow e}\ \Lambda\text{-EAp}$$

(b) Dynamic semantics

Figure: The untyped λ-calculus

Table of Contents

The Hazel programming language and environment

Live programming Rapid static and dynamic feedback ("gap problem")

Structured editor Elimination of syntax errors

Bidirectionally typed Simple type inference

Gradually typed Hole type and cast-calculus based on Siek et al. [1, 2]

Purely functional Avoids side-effects and promotes commutativity

(a) The Hazelgrove organization

(b) Implemented in ReasonML and JSOO

Figure: Hazel implementation

The Hazel programming interface

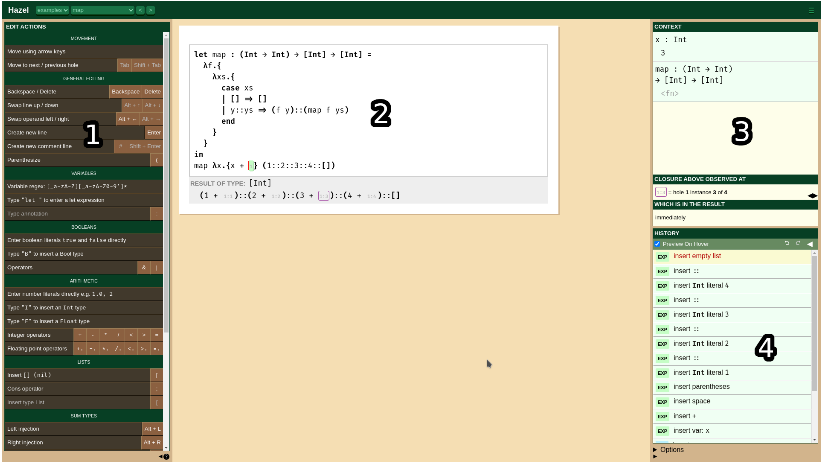


Figure: The Hazel interface

Hazelnut: A bidirectionally-typed static semantics

(Typed) expression holes Internalize "red squiggly underlines"

Action semantics Structural editing behavior, ensures always well-typed

#	Z-Expression	Next Action	Rule
1	$\triangleright\llparenthesis\rrparenthesis\triangleleft$	`construct lam` x	(13e)
2	$(\lambda x.\llparenthesis\rrparenthesis) : (\triangleright\llparenthesis\rrparenthesis\triangleleft \to \llparenthesis\rrparenthesis)$	`construct num`	(12b)
3	$(\lambda x.\llparenthesis\rrparenthesis) : (\triangleright\mathtt{num}\triangleleft \to \llparenthesis\rrparenthesis)$	`move parent`	(6c)
4	$(\lambda x.\llparenthesis\rrparenthesis) : \triangleright(\mathtt{num} \to \llparenthesis\rrparenthesis)\triangleleft$	`move child 2`	(6b)
5	$(\lambda x.\llparenthesis\rrparenthesis) : (\mathtt{num} \to \triangleright\llparenthesis\rrparenthesis\triangleleft)$	`construct num`	(12b)
6	$(\lambda x.\llparenthesis\rrparenthesis) : (\mathtt{num} \to \triangleright\mathtt{num}\triangleleft)$	`move parent`	(6d)
7	$(\lambda x.\llparenthesis\rrparenthesis) : \triangleright(\mathtt{num} \to \mathtt{num})\triangleleft$	`move parent`	(8d)
8	$\triangleright(\lambda x.\llparenthesis\rrparenthesis) : (\mathtt{num} \to \mathtt{num})\triangleleft$	`move child 1`	(8a)
9	$\triangleright(\lambda x.\llparenthesis\rrparenthesis)\triangleleft : (\mathtt{num} \to \mathtt{num})$	`move child 1`	(8e)
10	$(\lambda x.\triangleright\llparenthesis\rrparenthesis\triangleleft) : (\mathtt{num} \to \mathtt{num})$	`construct var` x	(13c)
11	$(\lambda x.\triangleright x\triangleleft) : (\mathtt{num} \to \mathtt{num})$	`construct plus`	(13l)
12	$(\lambda x.(x + \triangleright\llparenthesis\rrparenthesis\triangleleft)) : (\mathtt{num} \to \mathtt{num})$	`construct lit 1`	(13j)
13	$(\lambda x.(x + \triangleright\underline{1}\triangleleft)) : (\mathtt{num} \to \mathtt{num})$	—	—

Figure 1. Constructing the increment function in Hazelnut.

now assume $incr : \mathtt{num} \to \mathtt{num}$

#	Z-Expression	Next Action	Rule
14	$\triangleright\llparenthesis\rrparenthesis\triangleleft$	`construct var` *incr*	(13c)
15	$\triangleright incr\triangleleft$	`construct ap`	(13h)
16	$incr(\triangleright\llparenthesis\rrparenthesis\triangleleft)$	`construct var` *incr*	(13d)
17	$incr(\llparenthesis\triangleright incr\triangleleft\rrparenthesis)$	`construct ap`	(13h)
18	$incr(\llparenthesis incr(\triangleright\llparenthesis\rrparenthesis\triangleleft)\rrparenthesis)$	`construct lit 3`	(13j)
19	$incr(\llparenthesis incr(\triangleright\underline{3}\triangleleft)\rrparenthesis)$	`move parent`	(8j)
20	$incr(\llparenthesis\triangleright incr(\underline{3})\triangleleft\rrparenthesis)$	`move parent`	(8p)
21	$incr(\triangleright\llparenthesis incr(\underline{3})\rrparenthesis\triangleleft)$	`finish`	(16b)
22	$incr(\triangleright incr(\underline{3})\triangleleft)$	—	—

Figure 2. Applying the increment function.

Figure: Sample Hazelnut action sequence [3]

Hazelnut Live: A bidirectionally-typed dynamic semantics

Internal language Cast calculus from Siek et al. [1, 2] for dynamic typing

Hole evaluation Evaluation continues *around* holes, captures environment

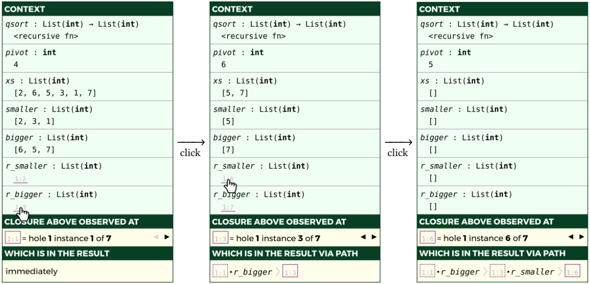


Figure: Illustration of Hazelnut Live context inspector [4]

Table of Contents

Evaluation using environments vs. substitution

[TODO: comparison table, illustration of how each one works]

Updated evaluation rules

$\boxed{\sigma \vdash d \Downarrow d'}$ d evaluates to d' given environment σ

$$\frac{}{\sigma \vdash (\lambda x : \tau.d) \Downarrow [\sigma](\lambda x : \tau.d')} \text{ ELam}$$

$$\frac{}{\sigma, x \leftarrow d \vdash x \Downarrow d} \text{ EVar}$$

$$\frac{\sigma \vdash d_1 \Downarrow [\sigma']\lambda x : \tau.d_1' \qquad \sigma \vdash d_2 \Downarrow d_2' \qquad \sigma', x \leftarrow d_2' \vdash d_1' \Downarrow d}{\sigma \vdash d_1 \ d_2 \Downarrow d} \text{ EAp}$$

$$\frac{}{\sigma \vdash (\!|\,|\!)^u \Downarrow [\sigma](\!|\,|\!)^u} \text{ EvalB-EHole} \qquad \frac{\sigma \vdash d \Downarrow d'}{\sigma \vdash (\!|d|\!)^u \Downarrow [\sigma](\!|d'|\!)^u} \text{ EvalB-NEHole}$$

Figure: Big-step semantics for evaluation with environments

Handling recursion

Fixpoint form Useful for a pure implementation of recursive functions, from Plotkin's System PCF

$$\frac{\sigma \vdash d \Downarrow [\sigma']d'}{\sigma \vdash \mathsf{fix}\, f : \tau.d \Downarrow [\sigma, f \leftarrow \mathsf{fix}\, f : \tau.[\sigma']d']d'} \text{ EFix}$$

$$\frac{d \neq \mathsf{fix}\, f : \tau.d'}{\sigma, x \leftarrow d \vdash x \Downarrow d} \text{ EVar} \qquad \frac{\sigma \vdash \mathsf{fix}\, f : \tau.d \Downarrow d'}{\sigma, x \leftarrow \mathsf{fix}\, f : \tau.d \vdash x \Downarrow d'} \text{ EUnwind}$$

Figure: Big-step semantics for evaluation of fixpoints

Matching the result from evaluation using substitution

$\boxed{d \Uparrow_{[]} d'}$ d is substitutes to d' inside the evaluation boundary

$$\frac{}{c \Uparrow_{[]} c}\ \text{PPI}_{[]}\text{Const} \qquad \frac{d_1 \Uparrow_{[]} d_1' \qquad d_2 \Uparrow_{[]} d_2'}{d_1\ d_2 \Uparrow_{[]} d_1'\ d_2'}\ \text{PPI}_{[]}\text{Ap} \qquad \frac{\sigma \Uparrow_{[]} \sigma' \qquad \sigma' \vdash d \Uparrow_{[]} d'}{[\sigma]d \Uparrow_{[]} d'}\ \text{PPI}_{[]}\text{Closure}$$

$\boxed{\sigma \vdash d \Uparrow_{[]} d'}$ d substitutes to d' outside the evaluation boundary

$$\frac{}{c \Uparrow_{[]} c}\ \text{PPO}_{[]}\text{Const} \qquad \frac{}{\sigma, x \leftarrow d \vdash x \Uparrow_{[]} d}\ \text{PPO}_{[]}\text{BoundVar} \qquad \frac{x \notin \sigma}{\sigma, \vdash x \Uparrow_{[]} x}\ \text{PPO}_{[]}\text{UnboundVar}$$

$$\frac{\sigma \vdash d \Uparrow_{[]} d'}{\sigma \vdash \lambda x.d \Uparrow_{[]} \lambda x.d'}\ \text{PPO}_{[]}\text{Lam} \qquad \frac{\sigma \vdash d_1 \Uparrow_{[]} d_1' \qquad \sigma \vdash d_2 \Uparrow_{[]} d_2'}{\sigma \vdash d_1(d_2) \Uparrow_{[]} d_1'(d_2')}\ \text{PPO}_{[]}\text{Ap}$$

$$\frac{}{\sigma \vdash (\!|\,|\!)^u \Uparrow_{[]} [\sigma](\!|\,|\!)^u}\ \text{PPO}_{[]}\text{EHole} \qquad \frac{\sigma \vdash d \Uparrow_{[]} d'}{\sigma \vdash (\!|d|\!)^u \Uparrow_{[]} [\sigma](\!|d'|\!)^u}\ \text{PPO}_{[]}\text{NEHole}$$

Figure: Big-step semantics for substitution postprocessing

Generalized closures

Interpretation	Sample expression
Function closure	$[\sigma]\lambda x.d$
Hole closure	$[\sigma]⦇d⦈^u$
Closure around unmatched `let`	$[\sigma](\texttt{let}\ x = d_1\ \texttt{in}\ d_2)$
Closure around unmatched `case`	$[\sigma](\texttt{case}\ x\ \texttt{of}\ \text{rules})$
Closure around filled hole	$[\![\sigma]\!]d_{fill}$

Table: Examples of generalized closures

Table of Contents

Motivation for hole instances

```
let a = ⦇⦈¹ in
let b = λ x . { ⦇⦈² } in
f 3 + f 4
```

Figure: Illustration of hole instances

$$[a \leftarrow [\varnothing]⦇⦈^1, x \leftarrow 3]⦇⦈^2 + [a \leftarrow [\varnothing]⦇⦈^1, x \leftarrow 4]⦇⦈^2$$

Figure: Result of Figure 11

Motivation for hole closures/instantiations I

$$
\begin{array}{l}
\texttt{let a = } (\!|\,|\!)^{1} \texttt{ in} \\
\texttt{let b = } (\!|\,|\!)^{2} \texttt{ in} \\
\texttt{let c = } (\!|\,|\!)^{3} \texttt{ in} \\
\texttt{let d = } (\!|\,|\!)^{4} \texttt{ in} \\
\texttt{let e = } (\!|\,|\!)^{5} \texttt{ in} \\
\texttt{let f = } (\!|\,|\!)^{6} \texttt{ in} \\
\texttt{let g = } (\!|\,|\!)^{7} \texttt{ in} \\
\texttt{...} \\
\texttt{let x = } (\!|\,|\!)^{n} \texttt{ in} \\
(\!|\,|\!)^{n+1}
\end{array}
$$

Figure: A Hazel program that generates 2^N total hole instances

Motivation for hole closures/instantiations II

$$
\begin{tikzcd}
{[\sigma^4]\llparenthesis\rrparenthesis^{4}} \arrow[d, "c"'] \arrow[dd, bend left, "b"] \arrow[ddd, bend left=60, "a"] \\
{[\sigma^3]\llparenthesis\rrparenthesis^{3}} \arrow[d, "b"'] \arrow[dd, bend right=60, "a"'] \\
{[\sigma^2]\llparenthesis\rrparenthesis^{2}} \arrow[d, "a"'] \\
{[\varnothing]\llparenthesis\rrparenthesis^{1}}
\end{tikzcd}
$$

(a) Structure of the result

$$
\begin{tikzcd}
 & & & {[\sigma^4]\llparenthesis\rrparenthesis^{4:1}} \arrow[dlll, "a"'] \arrow[dll, "b"] \arrow[d, "c"'] \\
{[\varnothing]\llparenthesis\rrparenthesis^{1:1}} & {[\sigma^2]\llparenthesis\rrparenthesis^{2:1}} \arrow[d, "a"'] & & {[\sigma^3]\llparenthesis\rrparenthesis^{3:1}} \arrow[dl, "a"'] \arrow[d, "b"'] \\
 & {[\varnothing]\llparenthesis\rrparenthesis^{1:2}} & {[\varnothing]\llparenthesis\rrparenthesis^{1:3}} & {[\sigma^2]\llparenthesis\rrparenthesis^{2:2}} \arrow[d, "a"'] \\
 & & & {[\varnothing]\llparenthesis\rrparenthesis^{1:4}}
\end{tikzcd}
$$

(b) Numbered hole instances in the result

Figure: Hole numbering in Figure 13

The hole numbering algorithm

$\boxed{H, p \vdash d \Uparrow_i d' \dashv H'}$ d gets renumbered to d'

$$\frac{(u, e) \notin H \qquad i = \mathrm{hid}(H, u) \qquad H, (u, i) \vdash \sigma \Uparrow_i \sigma' \dashv H' \qquad H'' = H, (u, e) \leftarrow (i, \{p\}, \sigma')}{H, p \vdash [\sigma^e]\llparenthesis\rrparenthesis^u \Uparrow_i [\sigma'^e]\llparenthesis\rrparenthesis^{u:i} \dashv H''} \text{ PP}_i\text{EHoleNew}$$

$$\frac{H = H', (u, e) \leftarrow (i, \{p_i\}, \sigma'^e) \qquad H'' = H, (u, e) \leftarrow (i, \{p_i\} \cup \{p\}, \sigma'^e)}{H, p \vdash [\sigma^e]\llparenthesis\rrparenthesis^u \Uparrow_i [\sigma'^e]\llparenthesis\rrparenthesis^{u:i} \dashv H''} \text{ PP}_i\text{EHoleFound}$$

$$\frac{\begin{array}{c}(u, e) \notin H \qquad i = \mathrm{hid}(H, u) \\ H, (u, e), \vdash \sigma \Uparrow_i \sigma' \dashv H' \qquad H'' = H, (u, e) \leftarrow (i, \{p\}, \sigma') \qquad H'', p \vdash d \Uparrow_i d' \dashv H'''\end{array}}{H, p \vdash [\sigma^e]\llparenthesis d\rrparenthesis^u \Uparrow_i [\sigma'^e]\llparenthesis d'\rrparenthesis^{u:i} \dashv H'''} \text{ PP}_i\text{NEHoleNew}$$

$$\frac{\begin{array}{c}H = H', (u, e) \leftarrow (i, \{p_i\}, \sigma'^e) \\ H'' = H, (u, e) \leftarrow (i, \{p_i\} \cup \{p\}, \sigma'^e) \qquad H'', p \vdash d \Uparrow_i d' \dashv H'''\end{array}}{H, p \vdash [\sigma^e]\llparenthesis d\rrparenthesis^u \Uparrow_i [\sigma'^e]\llparenthesis d'\rrparenthesis^{u:i} \dashv H'''} \text{ PP}_i\text{NEHoleFound}$$

Figure: Hole closure numbering postprocessing semantics

A unified postprocessing algorithm

$\boxed{d \Uparrow (H, d')}$ d postprocesses to d' with hole closure info H

$$\frac{d \Uparrow_{[]} d' \qquad \varnothing, \varnothing \vdash d' \Uparrow_i d'' \dashv H}{d \Uparrow d'' \dashv H}\ \text{PP-Result}$$

Figure: Overall postprocessing judgment

Table of Contents

Motivating example

The FAR process

1-step vs. n-step FAR

Detecting a valid fill operation

The fill operation

The resume operation

The postprocessing operation

Table of Contents

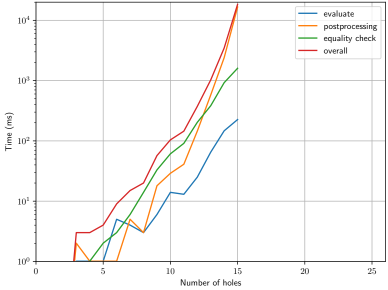
Evaluation with environments

Hole numbering motivating example I

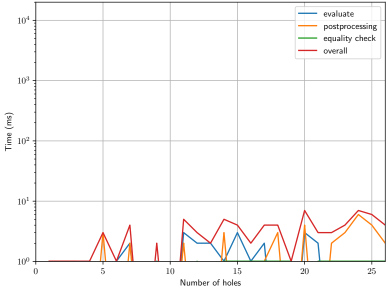
```
let a = ⦇⦈^1 in
let b = ⦇⦈^2 in
let c = ⦇⦈^3 in
let d = ⦇⦈^4 in
let e = ⦇⦈^5 in
let f = ⦇⦈^6 in
let g = ⦇⦈^7 in
...
let x = ⦇⦈^n in
⦇⦈^{n+1}
```

Figure: A Hazel program that generates 2^N total hole instances

Hole numbering motivating example II



(a) `dev` branch



(b) `eval-environment` branch

Figure: Performance of evaluating program in Figure 13

FAR motivating example I

Program	Steps	Steps (w/ FAR)	Step Δ	Cumulative Step Δ

`let f = ... in`
`let a =` $\llparenthesis\rrparenthesis^{1}$ `in`
$\llparenthesis\rrparenthesis^{2}$
	7	-	0	0

`let f = ... in`
`let a = f in`
$\llparenthesis\rrparenthesis^{2}$
	12	21	9	9

`let f = ... in`
`let a = f` $\llparenthesis\rrparenthesis^{3}$ `in`
$\llparenthesis\rrparenthesis^{2}$
	17	-	0	9

`let f = ... in`
`let a = f 2 in`
$\llparenthesis\rrparenthesis^{2}$
	58	69	11	20

Table: A program edit history with an expensive computation

FAR motivating example II

Program	Steps	Steps (w/ FAR)	Step Δ	Cumulative Step Δ

`let f = ... in`
`let a = f 25 in`
⦇⦈^{2}
	4762964	-	0	20

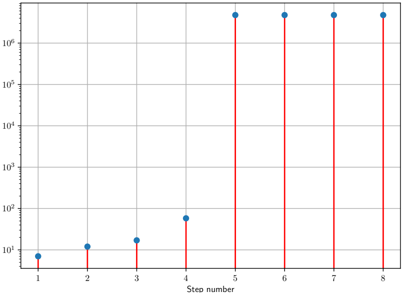
`let f = ... in`
`let a = f 25 in`
⦇⦈^{2} + ⦇⦈^{4}
	4762966	12	-4762954	-4762934

`let f = ... in`
`let a = f 25 in`
⦇⦈^{2} + 2
	4762966	21	-4762954	-9525879

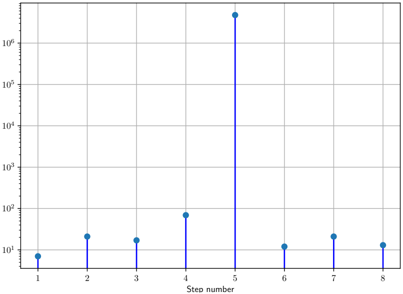
`let f = ... in`
`let a = f 25 in`
`a + 2`
	4792967	13	-4792954	-14288813

Table: A program edit history with an expensive computation, cont'd.

FAR motivating example III



(a) Normal evaluation



(b) With one-step FAR

Figure: Number of evaluation steps per edit in Table 2

Table of Contents

Generalized closures

Unique hole closures

FAR as a generalization of evaluation

Table of Contents

Future work

n-step FAR
: Integrate edit history into FAR

Generalized memoization
: Unify notation and metatheory of memoization

Formal evaluation of metatheory
: Check coverage and correctness of metatheorems using Agda

Conclusions

Evaluation with environments Expected performance gains, implementation remains functionally pure

Generalized closures Simplify many parts of the implementation, also useful for FAR

Memoization of environments Applicable for postprocessing, equality checking, resume operation

FAR PoC Including *n*-step detection, re-evaluation of closures

Plausible metatheory For future work in Agda

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