Revisiting the Futamura Projections:  
A Visual Analysis

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Abstract

The advent of language implementation tools such as PyPy have broadened interest in topics related to automatic compiler generation and optimization. Given this broader interest, we revisit the Futamura Projections using a diagram scheme. Through these diagrams we emphasize the recurring patterns in the Futamura Projections while addressing their complexity and abstract nature. We anticipate that this approach will improve the accessibility of the Futamura Projections and help foster analysis of those new tools through the lens of partial evaluation.

Keywords: compilation, compiler generation, Futamura Projections, interpretation, partial evaluation, program transformation.

1 Introduction

The Futamura Projections are a series of program signatures reported by [Fut99] (a reprinting of [Fut71]) designed to create a program that generates compilers. This is accomplished by repeated applications of a partial evaluator that iteratively abstract away aspects of the program execution process. A partial evaluator transforms a program given any subset of its input to produce a version of the program that has been specialized to that input. The partial evaluation operation is referred to as mixed computation because partial evaluation involves a mixture of interpretation and code generation [Ers77]. In this paper, we will provide an overview of typical program processing and discuss the Futamura Projections.
Table 1: Legend of symbols and terms used in § 2 and § 3.

| Symbol                  | Description                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| program                | A miscellaneous program.                                                   |
| $p_1$                  | A parameter.                                                               |
| $a_n$                  | An argument.                                                               |
| pow                    | A power program.                                                           |
| compiler$_{S\rightarrow T}$ | A compiler from language $S$ to language $T$, implemented in $T$.          |
| program$_S$            | A miscellaneous program implemented in language $S$.                      |
| program$_T$            | A miscellaneous program implemented in language $T$.                      |
| compiler$_{C\rightarrow x86}$ | A compiler from C to x86, implemented in x86.                            |
| pow$_C$                | A power program implemented in C.                                          |
| pow$_{x86}$            | A power program implemented in x86.                                        |
| interpreter$_S^T$      | An interpreter for language $S$ implemented in language $T$.               |
| interpreter$_{x86}^T$  | An interpreter for C implemented in x86.                                    |
| partial input$_{static}$ | A subset of input for a program being specialized by mix.                 |
| program$_T$            | A specialized program implemented in language $T$.                        |
| square$_{x86}$         | A square program implemented in x86.                                       |
| mix$_T$                | A partial evaluator implemented in language $T$.                          |
| mix$_{x86}$            | A partial evaluator implemented in language x86.                          |
| compiler generator$_T$ | A compiler generator implemented in language $T$.                         |
| compiler generator$_{x86}$ | A compiler generator implemented in x86.                                  |

2 Programs Processing Other Programs

We use notation in this paper for partial evaluation and associated programming language concepts from [JGS93, Jon96]. That notation is commonly used in papers on partial evaluation [Glü09, Thi96]. In particular, we use $[\cdot]$ to denote a semantics function which represents the evaluation of a program by mapping that program’s input to its output. For instance, $[p][s, d]$ represents the program $p$ applied to the inputs $s$ and $d$. We use the symbol $\text{mix}$ to denote the partial evaluation operation [JGS93, Jon96], which involves a mixture of interpretation and code generation. Table 1 is a legend mapping terms and symbols used in this article to their description.

Program execution can be represented equationally as $[\text{program}][a_1, a_2, \ldots, a_n] = [\text{output}]$ [JGS93]. Alternatively, the diagram in Fig. 1 depicts a program as a machine that takes a collection of input boxes, marked by divided slots of the input bar, and produces an output box. We use this diagram syntax to aid in the presentation of complex relationships between programs, inputs, and programs treated as inputs (i.e., data). Each input area corresponds to part of a C-function-style signature that names and positions the inputs. The input is presented in gray to distinguish it from the program and its input bar. Fig. 1b shows this pattern applied to a program that takes a base $b$ and an exponent $e$ and raises the base to the power of the exponent. In this case, $3$ raised to the power of $2$ produces $9$, or $[\text{pow}][3, 2] = 9$. 
2.1 Compilation

Programs written in higher-level programming languages such as C must be either compiled to a natively runnable language (e.g., the x86 machine language) or evaluated by an interpreter. A compiler is simply a program that translates a program from its source language to a target language. This process is described equationally as \([\text{compiler}_S^{S \rightarrow T}] \cdot \text{program}_S = \text{program}_T\), or diagrammatically in Fig. 2a. For clarity, the implementation language appears as a subscript of any program name. Compilers will also have a superscript with an arrow from the source (input) language to the target (output) language. If language \(T\) is natively executable, both the depicted compiler and its output program are natively executable. If \(\text{pow}\) from Fig. 1b is written in C, it can be compiled to the x86 machine language with a compiler as depicted in Fig. 2b or expressed equationally as \([\text{compiler}_C^{C \rightarrow x86}] \cdot \text{pow} \cdot \text{c} = \text{pow} \cdot \text{x86}\). Figs. 2c and 2d illustrate that the source and the target programs are semantically equivalent.

2.2 Interpretation

The gap between a high-level source language and a natively executable target language can also be bridged with the use of an interpreter. “The interpreter for a computer language is just another program” implemented in the target language that evaluates the program given the program’s input and producing its output \([\text{FW08}]\). The interpretation pattern, described equationally as...
(a) The compilation process.

(b) Compilation example.

(c) Comparison of compiler input and output.

(d) Comparison of compiler example input and output.

Figure 2: Execution through compilation.
(a) The interpretation process.

(b) Instance of program interpretation.

Figure 3: Execution by interpretation.

\[[\text{interpreter}^C][\text{program}_S, \text{input}]=[\text{output}]\], is depicted in Fig. 3a. The interpreter has the previously established implementation language subscript, with a superscript indicating the interpreted language. The input program’s input bar extends into the interpreter’s next input slot, which serves to indicate which individual input is associated with each of the program’s own input slots. However, as the inputs are actually being provided directly to the interpreter, an outline is drawn around each input to the program being executed. By convention, the background shading is alternated to differentiate inputs, while the borders of inputs remain gray. This pattern is applied to the \text{pow.c} program in Fig. 3b; the C program is being executed by an interpreter implemented in x86 to produce the output from \text{pow.c} given its input. This interpretation is represented equationally as \[[\text{interpreter}^C_{\text{x86}}][\text{pow.c}, 3, 2]=[9]\].

2.3 Partial Evaluation

With typical program evaluation, complete input must be provided during program execution. With partial evaluation, on the other hand, partial input—referred to as static input—is given in advance of program execution. This partial input is given with the program to be specialized to \text{mix}. The specialized/transformed program then accepts only the remaining input—referred to as the dynamic input—and produces the same output as would have been produced by running the original program with complete input. For reasons explained below, the Futamura Projections require that \text{mix} be implemented in the same language as the program it takes as input; diagrams including \text{mix} provide a subscript that represents the implementation language as well as the
(a) The partial evaluation process.

(b) Partial evaluation output.

(c) Instance of partial evaluation.

(d) Output of partial evaluation instance.

Figure 4: Partial evaluation.
language of the input and output programs.

Partial evaluation is described equationally as $[\text{mix}_T][\text{program}_T, \text{partial input}_{\text{static}}] = [\text{program}'_T]$ and depicted in Fig. 4a. Here, a program is being passed to mix with partial input—specifically, only its second argument.

The result is a transformed version of the program specialized to the input; the input has been propagated into the original program to produce a new program. This specialized transformation of the input program is called a residual program [Ers77]. Notice how the shape of the residual program mirrors the shape of the input program combined with the static input. Notice also in Fig. 4b that the shape of the program combined with the remainder of its input mirrors the shape of the typical program execution shown in Fig. 1a. However, the input has been visually fused to the program, represented by the dotted line. In addition, the labels for the original program, the second input slot, and the static input have been shaded gray; while the residual program is entirely comprised of these two components, its input interface has been modified to exclude them. In other words, while the components are still present, they are only in the background of the new program. The equational representation of this residual program shows the simplicity of its behavior: $[\text{program}'_T][a_1, a_3, ..., a_n] = [\text{output}]$.

The partial evaluation pattern is applied to the power program in Fig. 4c. If power is partially evaluated with static input $e = 2$, the result is a power program that can only raise a base to the power 2. This example is represented equationally as $[\text{mix}_{\text{x86}}][\text{power}_{\text{x86}}, e=2] = [\text{square}_{\text{x86}}]$. The specialization produces a program that takes a single input (as in Fig. 4d and $[\text{square}_{\text{x86}}][3] = [9]$) and squares it. It behaves as a squaring program despite being comprised of a power program and an input; mix has propagated the input into the original program to produce a specialized residual program.

### 3 The Futamura Projections

#### 3.1 First Futamura Projection: Compilation

Partial evaluation is beneficial given a program that will be executed repeatedly with some of its input constant, resulting in a significant speedup. For example, if squaring many values, a specialized squaring program prevents the need for repeated exponent $e = 2$ arguments. Program interpretation is another case that benefits from partial evaluation; after all, the interpreter is a program and the source program is a subset of its input. Fig. 5a illustrates that when given programs and an interpreter for $\mathcal{S}$ implemented in language $T$, we can partially evaluate the interpreter with the source program as static input (i.e., $[\text{mix}_T][\text{interpreter}_{\text{T}}, \text{programs}_{\mathcal{S}}] = [\text{program}_{\mathcal{T}}]$). This is the First Futamura Projection. As with the previous pattern, the partially evaluated program (i.e., the interpreter) has been specialized to the partial input (i.e., the source program), which is indicated visually by the fusion of the source program to the interpreter. Notice that $\text{programs}_{\mathcal{S}}$ is vertically aligned with the

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Figure 5: The First Futamura Projection and example instance.
static input slot of the partial evaluator as well as the program input slot of the interpreter. This is because \( \text{program}_S \) serves both roles. In this case, the dynamic input of the interpreter is the entirety of the input for \( \text{program}_S \). When that input is provided in Fig. 5c, the specialized program completes the interpretation of \( \text{program}_S \), producing the output for \( \text{program}_S \). In other words, the specialized program behaves exactly the same as \( \text{program}_S \), but is implemented in \( T \) rather than \( S \). The partial evaluator has effectively compiled the program from \( S \) to \( T \). Thus, the equational form is identical to that of a compiled program: \( [\text{program}_T] [a_1, a_2, ..., a_n] = [\text{output}] \). Fig. 5b and equation \( [\text{mix}_{\text{x86}}][\text{interpreter}_{\text{x86}}, \text{pow.c}] = [\text{pow}_{\text{x86}}] \) express the partial evaluation of a C interpreter when given \( \text{pow} \) as partial input. The residual program, detailed in Fig. 5d, behaves the same as \( \text{pow.c} \), but is implemented in x86. The equational expression for the target program is also identical to the compiled program: \( [\text{pow}_{\text{x86}}][3, 2] = [9] \).

**First Futamura Projection:** A partial evaluator, with an interpreter as input, can compile from the interpreted language to the implementation language of \( \text{mix} \).

### 3.2 Second Futamura Projection: Compiler Generation

The First Futamura Projection relies on the nature of interpretation requiring two types of input: a program that may be executed multiple times, and input for that program that may vary between executions. As it turns out, the use of \( \text{mix} \) as a compiler exhibits a similar signature: the interpreter is specialized multiple times with different source programs. This allows us to partially evaluate the process of compiling with a partial evaluator. This is the **Second Futamura Projection**, represented equationally as \( [\text{mix}_T][\text{mix}_T, \text{interpreter}_T] = [\text{compiler}_T^{S \rightarrow T}] \) and depicted in Fig. 6a. In this partial-partial evaluation pattern, an instance of \( \text{mix} \) is being provided as the program input to another instance of \( \text{mix} \), to which an interpreter is provided as static input. Just as in earlier partial evaluation patterns, the program input has been specialized to the given static input; in this case, an instance of \( \text{mix} \) is being specialized to the interpreter. The vertical alignment of programs helps clarify the roles of each program present: the interpreter is the partial input given to the executing instance of \( \text{mix} \) as well as the program input given to the specialized instance of \( \text{mix} \). Additionally, this **specialized residual program as executed in Fig. 6b matches the shape and behavior of the First Futamura Projection shown in Fig. 5a**. This is because the same program is being executed with the same input; the only difference is that the output of the second projection is a single program that has been specialized to the interpreter rather than a separate \( \text{mix} \) instance that requires the interpreter to be provided as input. In the Second Futamura Projection, \( \text{mix} \) has generated the \( \text{mix} \)-based compiler from the first projection. Because the residual program is a compiler, its equational expression is that of a compiler: \( [\text{compiler}_T^{S \rightarrow T}][\text{program}_S] = [\text{program}_T] \).

Revisiting the \( \text{pow.c} \) program in Figs. 6c and 6d, \( \text{mix} \) is specialized to a C
(a) The Second Futamura Projection.

(b) The output of the Second Futamura Projection.

(c) An instance of the Second Futamura Projection.

(d) The output of the Second Futamura Projection instance.

Figure 6: The Second Futamura Projection and example instance.
interpreter to produce a C compiler (i.e., \([ \text{mix}_{x86} \text{mix}_{x86}, \text{interpreter}_{x86} ] = [\text{compiler}_{x86} ]\)). When given \(\text{pow}\) in C, this specialized \text{mix}\) program then specializes the interpreter to \(\text{pow}\), producing an equivalent power program in x86 ([\text{compiler}_{x86} [\text{pow}.c] = [\text{pow}_{x86}])).

**Second Futamura Projection:** A partial evaluator, by making use of itself and the interpreter, can generate a compiler from the interpreted language to the implementation language of \text{mix}.

### 3.3 Third Futamura Projection: Generation of Compiler Generators

Because \text{mix} can accept itself as input, we can use one instance of \text{mix} to partially evaluate a second instance of \text{mix}, passing a third instance of \text{mix} as the static input. This is the **Third Futamura Projection**, shown in Fig. 7a and written equationally as \([\text{mix}_T [\text{mix}]) = [\text{compiler generator}_T]\). The transformation itself is straightforward: partially evaluating a program with some input. The output is still the program in the first input slot specialized to the data in the second input slot; however, this time both the program...
(a) An instance of the Third Futamura Projection.

(b) The output of the Third Futamura Projection instance.

(c) The compiler generator generating a Perl compiler.

Figure 8: Instance of the Third Futamura Projection and output demonstration.
and the data are instances of mix. Again, the positioning of the various instances of mix within the diagram serves to clarify how the instances interact. The outermost instance executes with the other two instances as input. The middle instance is the “program” input of the outer instance and is specialized to the inner instance. Finally, the inner instance is being integrated into the middle instance by the outer instance. Notice that Fig. 7 shows that the execution of the residual program matches the shape and behavior of the Second Futamura Projection shown in Fig. 6a when provided with an interpreter as input. The partial evaluator has generated the mix-based compiler generator from the second projection. This process is represented equationally as 

\[ \text{compiler generator}_T [\text{interpreter}_C] = \text{compiler}_T. \]

Interestingly, the only variable part of the Third Futamura Projection is the language associated with mix. Previous instance diagrams were specific to the pow.c program; for instance, Fig. 6c presents an interpreter for the implementation language of pow.c, namely C. However, the diagram in Fig. 8a and the expression \[ \text{mix}_{\text{x86}} [\text{mix}_{\text{x86}}, \text{mix}_{\text{x86}}] = \text{compiler generator}_{\text{x86}} \]

make no reference to pow.c or C. This is because the Third Futamura Projection has abstracted the interpretation process to an extent that the interpreter is considered dynamic input. Fig. 8b shows the mix-generated compiler generator accepting a C interpreter and generating a C to x86 compiler \( (\text{compiler generator}_{\text{x86}}[\text{interpreter}_{\text{C}}]) = \text{compiler}_{\text{x86}} \)

but it will accept any interpreter implemented in x86 regardless of the language interpreted. For example, Fig. 8c shows a compiler for the language Perl being generated by the same compiler generator (i.e., \( \text{compiler generator}_{\text{x86}}[\text{interpreter}_{\text{Perl}}] = \text{compiler}_{\text{Perl}} \)). A residual compiler generated through the result of the Third Futamura Projection is called a generating extension—a term coined by Ershov [Ers77]—of the input interpreter [Thi96]. In general, the result of The Third Projection creates a generating extension for any program provided to it.

**Third Futamura Projection:** A partial evaluator, by making use of two other instances of itself, can generate a compiler generator that produces compilers from any language to the implementation language of mix.

### 3.4 Summary: Futamura Projections

The Third Futamura Projection follows the pattern of the previous two projections: the use of mix to partially evaluate a prior process (i.e., interpretation, compilation). The first projection compiles by partially evaluating the interpretation process without the input of the source program. The second projection generates a compiler by partially evaluating the compilation process from the first projection without any particular source program. The Third Futamura Projection generates a compiler generator by partially evaluating the compiler generation process without the interpreter. Each projection delays completion of the previous process by abstracting away the more variable of two inputs.
4 Discussion

4.1 Related Representations

A common syntax for presentation of program interpretation and transformation is the I (for interpreter) and T (for translator, meaning compiler) diagram, respectively [JGS93]. Fig. 9 illustrates the syntax of each diagram as well as an instance of each. An I diagram specifies the interpreted language above the implementation language. A T diagram represents a compiler by including an arrow from its source to target languages above its implementation language. The vertical alignment of input slots implicit in the syntax of the diagrams presented in this paper provides additional clarity for coordinating inputs through multiple layers of partial evaluation.

4.2 Examples of Partial Evaluators

Partial evaluators have been developed for several practical programming languages including C [And92], Scheme [BD91], and Prolog [MB93]. These partial...
Table 2: Juxtaposition of related equations and diagrams from § 2 and § 3.

| Fig. | Equational Notation | Input Description | Output Description | Similar Fig. | Output Fig. |
|------|---------------------|-------------------|--------------------|--------------|-------------|
| 3a   | program\(a_1, a_2, \ldots, a_n\) = \[output\]  | A list of arguments to the program.  | The result of the program's execution. | N/A          | N/A         |
| 3b   | compiler\(S→T\) \[program_S\] = [program_T]  | A program in language S.  | The input program in language T. | N/A          | 5a          |
| 3c   | interpreter\(S\), program\(S\) = [output]  | A program in language S, along with its input.  | The result of the program's execution. | N/A          | 5c          |
| 4a   | mix\(T\) \[program_T\] = \[output\]  | A program in language T.  | The result of the program's execution. | N/A          | N/A         |
| 4b   | mix\(S\), mix\(T\) \[a_1, a_2, \ldots, a_n\] = \[output\]  | A list of arguments to the original program, excluding the static input.  | The result of the original program's execution. | N/A          | N/A         |
| 5a   | mix\(T\) \[program_T\], interpreter\(S\) = [program_T]  | A program in language T and an interpreter for language S.  | The program implemented in T. | N/A          | 6a          |
| 5b   | mix\(S\), mix\(T\) \[a_1, a_2, \ldots, a_n\] = \[output\]  | A list of arguments to the original program.  | The result of the original program's execution. | N/A          | 6b          |
| 6a   | mix\(S\), mix\(T\) \[program_T\] = [program_T]  | A program in language T.  | The input program translated to the partial input. | N/A          | 7a          |
| 6b   | mix\(S\), mix\(T\) \[a_1, a_2, \ldots, a_n\] = \[output\]  | A list of arguments to the original program.  | The result of the original program's execution. | N/A          | 7b          |
| 7a   | mix\(S\), mix\(T\) \[program_T\] = [program_T]  | A program in language T.  | The input program translated to the partial input. | N/A          | 5a          |
| 7b   | mix\(S\), mix\(T\) \[a_1, a_2, \ldots, a_n\] = \[output\]  | A list of arguments to the original program.  | The result of the original program's execution. | N/A          | 5c          |

Table 3: Summary of Futamura Projections.

| Projection | Description | Equational Notation | Fig. | Output Fig. |
|------------|-------------|---------------------|------|-------------|
| 1          | mix can compile. | mix\(T\) \[\text{interpreter}\_{T}^{T}, \text{program}_{S}\] = [program_T] | 5a   | 5c          |
| 2          | mix can generate a compiler. | mix\(T\) \[mix_{T}, \text{interpreter}\_{T}^{T}\] = [compiler\(T\)] | 6a   | 6b          |
| 3          | mix can generate a compiler generator. | mix\(T\) \[mix_T, mix_T\] = [compiler generator\(T\)] | 7a   | 7b          |
evaluators are self-applicable and, thus, can perform all three Futamura Projections [Glu09].

4.3 Beyond the Third Projection

Researchers have studied what lies beyond the third projection and what significance the presence of a fourth projection might have [Glu09]. Two important conclusions have been made in this regard:

- Any self-generating compiler generator, i.e., a compiler generator such that,

  \[
  \text{[compiler generator]}[\text{mix}] = \text{compiler generator},
  \]

  can be obtained by repeated self-application of a partial evaluator as in the Third Futamura Projection, and vice versa.

- The compiler generator can be applied to another partial evaluator with different properties to produce a new compiler generator with related properties. For example, applying a compiler generator that accepts C programs to a partial evaluator accepting Python (but written in C) will produce a compiler generator that accepts Python programs.

These two observations are not orthogonal, but rather two sides of the same coin because they both depend on the application of a compiler generator to a partial evaluator. We refer the reader interested in further, formal exploration of these ideas and insights to [Glu09].

4.4 Related Approaches

We would be remiss not to mention the PyPy project (https://pypy.org/), which approaches the problem of optimizing interpreted programs from a different perspective. While named for its Python self-interpreter, the pertinent part of the project is its RPython translation toolchain. RPython is a framework designed for compiling high-level, dynamic language interpreters from a subset of Python to a selection of low-level languages such as C or bytecode. While PyPy does not generate compilers, it does add several features such as Just-In-Time compilation to the interpreters it processes [PyP16]. To demonstrate this, the PyPy self-interpreter, once compiled to C, outperforms the CPython interpreter in many performance tests [PyP].

The PyPy approach is attractive because it does not require a self-applicable, online\footnote{For a discussion of the difference between online and offline partial evaluation, see [MS07].} partial evaluator [LtPT07]. Such a partial evaluator would enable efficient self-generating compiler generators. However, to the best of our knowledge, such a self-applicable, online partial evaluator has not yet been developed.
4.5 Conclusion

The Futamura Projections can be used to compile, generate compilers, and generate compiler generators. We are optimistic that this article has demystified their esoteric nature. Increased attention for and broader awareness of this topic may lead to varied perspectives on language implementation and optimization tools like PyPy [Bol12a, Bol12b]. Additionally, further analysis may lead to new strides into the development of a practical partial evaluator that can effectively produce the Futamura Projections.

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