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Bachelor Thesis

Design and implementation of the Meta-Casanova 3 Compiler back-end

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1 Introduction

1 This project is about the development of the back-end of the bootstrap compiler for the Meta-Casanova 3 language. The back-end is responsible for generating an executable after receiving the type-checked information from the front-end.

2 Compilers are complex programs that have to operate on a wide range of inputs. Since compilers have such a large input-space, the chance of a bug hiding somewhere is substantial. But for all their complexity, compilers also have to be bug-free since every program can only be as bug-free as its compiler.

Abstractions can help in this regard. The limits of which were observed when implementing the compiler for the Casanova language in F#. The compiler was 0000 lines long, and became unmaintainable. After a rewrite in MC it was 000 lines[1].

The primary reason for this was the lack of higher-order type operators. This made abstractions such as monad-transformers impossible, hampering modularity and resulted in a lot of boilerplate code.

In this thesis, we will walk through the backend and examine the various parts and their design decisions. We will first discuss the context of the assignment. Then we will give a short overview of Meta Casanova. Research, The main part of is thesis, is next. It presents the main research question and splits it in subquestions. Each subquestion is answered in each subsection. The Results presents the proof that the requirements of the main research question have been met. This is followed by the conclusions that summarize the results. After the thesis proper, We give recommendations for the future development of the backend. The reflection is the last part of the thesis, and shows that the dublin descriptors have been met.

The appendices contain the contact details of the stakeholders, a glossary and the full source code of the backend.

2 Company

The graduation assignment is be carried out at Kenniscentrum Creating 010. The company is located in Rotterdam. *Kenniscentrum Creating 010 is a transdisciplinary design-inclusive Research Center enabling citizens, students and creative industry making the future of Rotterdam*[2].

The assignment is carried out within a research group, who is building a new programming language. The new programming language is called *Casanova*.

2.1 Goal

— short summary —

2.2 Motive

— Researching game development, Casanova needed, compiler difficult, MC needed, compiler needed —

2.3 Research team

— one student created the front-end, one tested the language —

3 Meta Casanova

It is necessary to understand a subset of Meta Casanova(MC) in order to understand the problem-space. This section will cover the subset of the language that is relevant for code-generation.

Meta Casanova is a functional, declarative language. It allows for multiple implementations of functions called *rules*. Rules may fail, in that case the next rule will be attempted. This will continue until a rule succeeds, or no rule matches in which case the program throws an exception.

3.1 Data

Data declarations declare a discriminated union.[**algebraic_datastructures**].

```
Data "nil" -> list<'a>
Data 'a -> ":@" -> list<'a> -> list<'a>
```

It defines the same structure as this F#-like pseudocode.

```
List<'a> = nil
| 'a :: List<'a>
```

In this example, the list type is declared with two constructors. They specify that a lists can be constructed in two ways: with `nil` and with `::` surrounded with a term of type `'a`, and a term of type `list<'a>`.

Conversely, they also specify that an list can be destructured in two ways. The programmer will assert which destructor is expected, and the rule fails if the destructor does not match. An example of this is shown later, in subsection “Funcs”.

Additionally, constructors may be manipulated and partially applied like functions. This allows for greater flexibility at the cost that function and constructor names need to be unique in their namespace.

3.2 Funcs

Func declarations specify a new function and its type.

```
Func "length" -> list<'a> -> int
```

As with constructors, functions may be freely manipulated and partially applied, and have the restriction that their name must be unique in their namespace.

3.3 Rules

Meta-Casanova uses a syntax similar to that of natural deduction. For each Func declaration, there are one or more rules that define it.

```
-----
length nil -> 0

length xs -> res
-----
length x::xs -> 1+res
```

A rule is comprised of a line with below it on the left of the arrow the input, and on the right the output. The statements above the horizontal line

are called *premises*. They can be assignments like in the example above, or conditionals like $a=b$ or $c<d$.

In the case of assignments, they create a *local identifier*. These identifiers are local to the rule they appear in. The input arguments of the rule are also local identifiers.

We can now call the function `length` with an example list:

```
1::(2::nil) -> x
length x    -> res
```

The first premise constructs a list called “x”, and the second statement calls `length` with that list. The program will execute as follows:

```
length 1::(2::nil)
  nil
  x::xs -> 1+(length 2::nil)
    nil
    x::xs -> 1+(length nil)
      nil -> 0
      x::xs
```

After which the function stops calling itself and starts accumulating the result on the way down.

```
1 -> 1+0
2 -> 1+1
2
```

After which it tells us correctly that the length of the list `1::(2::nil)` is indeed 2.

3.4 Main

Each program needs an entry point. The entry point of an MC program is the main function.

```
length 1::(2::nil) -> res
-----
main -> res
```

The results of the main function are printed on the console. The previous program would therefore print 2 on the screen.

4 Research

The primary research question of this thesis is:

¹see section 2.2

How to implement a transformation from type-checked Meta-Casanova(MC) to executable code within the timeframe of the internship?

Where the transformation must satisfy these requirements:

1. The backend must in no case produce an incorrect program.
2. The executable must be able to inter-operate with .NET.
3. The generated code must run on all the platforms .NET runs on.
4. The performance of the generated program should be comparable to Python.

The first requirement exists because the compiler must be reliable. Any program can at most be as reliable as the compiler used to generate it.

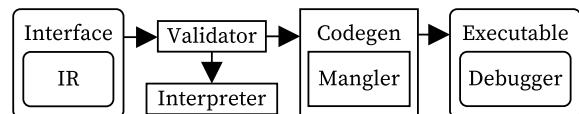
The second requirement existed because of the need for a large library and inter-operability with Unity game engine. This is because the main area of research of the organization is game-related¹.

In order to answer the research question, seven subquestions were formulated.

1. In what language should the code generator produce its output?
2. What should the interface be between the front-end and the back-end?
3. What should the intermediate representation of the functions be?
4. How does the interface map to the output language?
5. How to generate names so that they comply with the output language?
6. How to validate the code-generator?
7. How to validate the test programs?

Each answer of a subquestion is proven by implementing a part of the backend.

To illustrate how the different parts of the backend relate to each other, here is a diagram of the dataflow through the backend.



As you can see, the front-end interface contains the Intermediate Representation(IR) and goes through the validator. From there, depending on the compiler flags, it either goes to the interpreter or the codegen. In case it goes to the interpreter, the program is directly executed. In case it goes to the codegen, it is translated to the output language. To translate all the identifiers, the mangler is needed. The debugger is optionally embedded in the executable, depending on compiler flags.

4.1 Output language

The first research question had the most impact on the project, and was one that was difficult to change later on.

In what programming language should the code-generator produce its output?

This may be different than the language the code-generator is written in. The code-generator is written in F#, like the rest of the compiler. The reason we use F#, rather than Meta-Casanova 2, is because Meta Casanova 2 lacks tool support, such as descriptive error messages and debuggers.

Unmanaged languages

Since speed was one of the requirements, I first looked at solutions with unmanaged parts. Unmanaged code is code that is not interpreted by a runtime, but is instead executed directly.

The main advantage of unmanaged code is that the fast LLVM code generator can be used. LLVM is a “collection of modular and reusable compiler and toolchain technologies.”[3] Specifically, the LLVM optimizer is valuable. It is used in the Clang, a C/C++ compiler on par with gcc, and with little effort can be use it to optimize our generated code. This would mean we get all the optimisations of LLVM with relative ease. It would however mean that we had to implement a garbage collector, as LLVM does not come with one.

.NET compatibility is also required, as explained in section 4. There are a few systems that allow for managed and unmanaged code to communicate. The most viable are P/invoke, C++/CLI interop, and a hosted runtime.

P/invoke Platform Invocation Services allows managed code to call unmanaged functions that are implemented in a DLL.[4]

This is the most common form of inter-op, and has great documentation. However, there are two big disadvantages.

1. .NET can only call native functions, not the other way around. This means that the bulk of the control flow happens inside .NET, minimizing the fast native code.
2. Transferring data between .NET and native code has a high performance cost[5], since it has to be serialized. This overhead is so large that we expect it to negate any performance benefit from using native code.

Because of this, P/Invoke was not chosen.

C++/CLI C++ for the Common Language Infrastructure is a programming language designed for interoperability with unmanaged code.[msdn_cpluspluscli]

While it seems like it does exactly what we need, it has portability issues. The only C++/CLI compiler runs on windows and it only compiles for processors with the x86 architecture[6]. Besides that, non-typesafe operations (the main advantage of C++/CLI) are only allowed on windows.[6]

This means C++/CLI is not cross-platform enough.

Hosted runtime It is possible to embed a .NET runtime inside a native program. This would make it so the control flow takes place inside the native part.

This seems like the best solution out of the native hybrids. However it still has two drawbacks. The mono runtime has a different interface than the microsoft .NET api, leading to incompatible programs [7]. The same large serialization overhead as P/Invoke is present[8].

.NET languages

None of the inter-op methods offer a satisfactory solution. They all have downsides that outweigh the benefits. It was decided to let go of the LLVM code-generation in favor of a more portable and reliable system.

Stability is a big advantage because everything happens inside the .NET runtime. This has a higher chance of working on non-native platforms than the hybrid solutions.

F# is a functional/declarative language in the .Net family[.]. It would be a natural choice, since the compiler is written in it. It has the advantage of supporting tail-calls, which is unsupported by C#. And since F# already supported algebraic datatypes, it seemed like a viable solution.

C# is an imperative, object-oriented language[csharp]. It is the most popular .NET language[9], so the compiler gets the most attention by Microsoft. It is also easy to debug, as it has the most mature debugging tools. C# too seemed like a viable option.

CIL (Common Intermediate Language) is the bytecode that all the languages are compiled to. Since it is typed, it has the same restrictions as C#.source As a result, it makes debugging and verification harder, with little to no gain. It also ommits the optimizations of the C# compiler, such as dead-code elimination and stuff[csharp_optimizations].

Conclusion

The result of the research was that, C# and F# were both viable. To choose an output language, I built a code model for each language.

The F# code model mainly involved switching off indentation-based scoping for F# and using the verbose syntax. Scoping was implemented by making each rule a numbered function that returned an `Option<>`. the numbered rules were then called and appended using the `>>=` of the `Option` monad.

While this model worked, it was cumbersome and slow. The code was hard to inspect, since there was no indentation. It was also relatively slow because²

1. It had to wrap each return value in a `Option`. This is particularly costly for

value-types, as they have to be boxed and unboxed each time the value is used.

2. It perform monadic operations for each rule attempt. These generic functions do type resolution at run-time, each time they are called.
3. The numbered functions were not inlined, preventing any cross-rule optimization.

The C# code model proved far easier to generate and inspect, as it had braces and local scopes. It is the model that is now used³.

4.2 The front-end interface

The second research question is about the specification of the front-end interface.

What should the interface between the front-end and the back-end be?

The front-end interface contains all the input for the backend. This makes testing very easy, as the rest of the backend only relies on its input.

Interface

```
type Interface = {  
    datas      : List<Id*Data>  
    funcs      : List<Id*List<rule>>  
    lambdas    : List<LambdaId*rule>  
    main       : rule  
    flags      : CompilerFlags  
    assemblies : List<string>  
}
```

As you can see, the interface contains the data declarations, function definitions, lambda definitions and a main function.

The design principles for this interface were simplicity and minimalism. There should be as few ways as possible to represent the same program. This makes testing easier and minimizes bugs that appear only in certain representations of the same program.

All the symbols in the descriptions are provided with monomorphic types by the front-end. Functions with generic types are made concrete by the front-end.

²information obtained by inspecting generated CIL code of the microsoft F# compiler `fsc.exe` version 1.0 with `+optimize`

³see section 4.4

The reason that datas, funcs and lambdas are defined as a list of key-value pairs instead of as a Map, is that the keys are not guaranteed to be unique. Since MC allows polymorphic types, one identifier may be defined multiple times: once for each type. There is no performance penalty for the back-end, as no lookups by identifier are performed.

Data declarations

The data declarations are grouped with the identifier of the constructor.

```
datas : List<Id*Data>
```

Where Data is simply a list of input types and output types.

```
type Data = {  
  args      : List<Type>  
  outputType : Type  
}
```

Where Type represents a monomorphic MC type.

To illustrate, let's define a tuple and a union in MC.

```
Data int -> "," -> string -> Tuple<int  
  string>  
Data "fst" -> int -> Union<int string>  
Data "snd" -> string -> Union<int string>
```

This will appear as the following list in the interface:

identifier	arguments	type
","	int;string	Tuple<int string>
"fst"	int	Union<int string>
"snd"	string	Union<int string>

Rule containers

Function and lambda definitions, as well as the main function contain rules.

```
funcs   : List<Id*List<rule>>  
lambdas : List<LambdaId*rule>  
main    : rule
```

Functions in MC can contain multiple rules that implement them.

⁴see section 4.7

⁵see section 4.3

The entry point of the program is defined by a single rule, here called *main*. It is not a full function since full functions can have multiple rules. This was done to make the entry-point as simple as possible.

Rules

Functions are defined with one or more *rules*. This is how they are represented in the interface.

```
type rule = {  
  premises   : List<premise*lineno>  
  input      : List<local_id>  
  output     : local_id  
  typemap    : Map<local_id,Type>  
  declaration : Position  
  definition  : Position  
}
```

The main component of rules are their premises. They are the instructions that make up the rule. The instruction set is described in section 4.3.

The premise list also contains line numbers for each premise. This is debug information, that is used by the embedded debugger⁴.

Next are the inputs and output of the rule. Input and outputs consist only of local identifiers. This is because of *normalization*⁵.

In the case that a rule-input or output has an expression instead of a local identifier, the expression is assigned to a new local identifier and the local identifier is substituted.

The typemap contains a map from the local identifiers in a rule to their types. This gives the back-end all the information that the typechecker has accumulated.

The last two members are declaration and definition. These represent the position that the function was declared and the position that it was defined. This information is used by the debugger.

Validator

The first versions of the backend had no working front-end to test with. Early testing was done by

writing the interface datastructure by hand. Because that was error-prone, I implemented an automatic checker for the interface to check the invariants.

The validator asserts the following:

- Each local identifier is defined only once.
- Each local identifier has a type in the typemap.
- Each function has at least one rule.

The validator was initially only for validating hand-written interfaces, but it proved to be very good in catching errors that slipped through the front-end. The validator now always checks the interface before it is handed to the codegen.

4.3 Intermediate Representation

While the intermediate representation(IR) of the functions is part of the interface, it is complex enough to have its own research question.

What should the intermediate representation of the functions be?

Each rule contains a list of premises⁶. These premises represent the executable code in each rule.

To minimize the number of representations of the same program, all compound premises are split into multiple premises that do only one operation each. This process is called *normalization*.

The instruction set exists in two parts: the base instructions and the .NET extentions.

Base instructions

The instruction set was designed to minimize the number of representations of the same program. This happens to coincide with a small orthogonal instruction set.

The instruction set is in *static single assignment* (SSA) form. This means the local identifiers are constant and can not be redefined.

Base instructions fall in one of two groups. The first maps a global identifier to a local identifier. This are the Literal and Closure instructions. The

second operates on local identifiers. The Conditional, Deconstructor, Application and Call instructions belong to this group.

Literal (42 -> x) assigns a string-, boolean-, integer- or floating-point literal to a local identifier.

Conditional (x < y) asserts that a comparison between local identifiers is true. The comparisons can be <,<=,==,>=,> or !=. If the assertion fails, the rule fails and the next rule in the function is attempted.

Deconstructor (lst -> x::xs) disassembles a local identifier constructed by a data declaration.

Closure ((+) -> add) assigns a closure of a global function to a local identifier. The closure can hold a function, lambda or data-constructor.

Application (add a -> inc) applies a local identifier to a closure in another local identifier.

Call (inc b -> c) applies a local identifier and calls the closure. All closures need to be called eventually to be usefull. The exception is data-constructors. They do not have to be called as they insert their elements in the datastructure as they are applied.

.NET extentions

A separete set of instructions are needed to interoperate with .NET. This is because unlike MC, .NET objects are mutable, and the functions can be overloaded on the number and types of arguments.

instruction	MC example
-------------	------------

call	System.DateTime d m y -> date
static call	System.DateTime d m y -> date
get	System.DateTime d m y -> date
static get	System.DateTime d m y -> date
set	System.DateTime d m y -> date
static set	System.DateTime d m y -> date

⁶see section 3.3

Evolution

It was briefly considered to use an existing intermediate representation, like CIL or LLVM-IR. However, it would mean over 100 instructions and the front-end would do most of the work. It would also mean the front-end needed its own codegen to generate the CIL instructions.

Call did not used to apply an argument, but it caused inconsistencies in the type-checker. There would be not difference in the type of the uncalled closure and the called closure, resulting in an extra bit of information being required with the type. This caused special-cases all over the codebase, so it was decided to make application take an argument, like in lambda-calculus.

Application used to also take the position of the argument that was applied. This was because the backend did not care in what order the closures were applied. But since the MC language only allows for in-order closure application, the decision was made to make the position of the argument implicit to limit the program representations.

Comparisons could first only take a boolean local identifier. It was changed to a predefined set of comparisons because of two reasons. Firstly, it makes the language-agnostic base instructions depend on .NET Booleans. Secondly, by restricting the inputs to only a predefined set of comparisons, we restrict the number of representations for the same program.

4.4 Code generator

The fourth research question gets at the heart of the back-end.

How does the intermediate representation map to the output language?

The codegen is in many ways the heart of the back end, as it is responsible for generating the C# code.

Functions

Every function was implemented as a closure. In C# this means a class with a public field for each function argument and a `_run` function that

takes the last argument and executes the function.

```
class <function name> {
    <function arguments>
    public <return type>
    _run(<last argument>) {
        {
            <rule 1 implementation>
            return <local>;
        }
        skip1:
        {
            <rule 2 implementation>
            return <local>;
        }
        skip2:
        :
        {
            <rule n implementation>
            return <local>;
        }
        skipn:
        throw new <exception>;
    }
};
```

The `_run` function opens a local scope followed by a goto-label for each rule in the function. This allows rules to easily fail by jumping ahead to the label. More on rules ahead in subsection *rules*.

Data declarations

Data declarations are implemented with inheritance. The declared type is represented by an empty baseclass and all the constructors inherit from it.

This is a pretty straight-forward transformation.

```
Data string -> "," -> int -> string * int

Data "Left" -> string -> string | float
Data "Right" -> float -> string | float
```

The above MC code transforms into the following C# code.

```
class _star {};
class _comma { string _arg0; int _arg1;}

class _pipe {};
class _Left :_pipe {string _arg0;};
class _Right:_pipe {float _arg0;};
```

The types `_star` and `_pipe` can now be easily be deconstructed. When a premis deconstructs a datatype, it asserts that a type is constructed by a specific constructor. This is done by simply

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casting the base-class to a subclass, and checking if the cast succeeded. If the cast failed, the rule does not match and the rule is skipped.

Rules

Each rule defines its own name for each input argument. These names do not have to be the same, for example:

```
Func "evenOrOdd" -> int -> string

a%2 = 1
-----
evenOrOdd a -> "odd!"

b%2 = 0
-----
evenOrOdd b -> "even!"
```

Of course, by the time the code has arrived by the codegen, it would already have been normalized. So the rules actually look more like this:

```
(%) -> _tmp0      (closure)
_tmp0 a -> _tmp1   (application)
2 -> _tmp2         (literal)
_tmp1 _tmp2 -> _tmp3 (call)
0 -> _tmp4         (literal)
tmp4 = tmp0        (conditional)
"even" -> _tmp5    (literal)
-----
evenOrOdd a -> _tmp5

(%) -> _tmp0      (closure)
_tmp0 a -> _tmp1   (application)
2 -> _tmp2         (literal)
_tmp1 _tmp2 -> _tmp3 (call)
1 -> _tmp4         (literal)
tmp4 = tmp0        (conditional)
"odd" -> _tmp5     (literal)
-----
evenOrOdd a -> _tmp5
```

The first job of the rule is to translate the input arguments to their name and return the output.

```
{
    var a = _arg0;
    ...
    return _tmp5;
}
_skip0:
{
    var b = _arg0;
    ...
    return _tmp5;
}
_skip1:
```

Then each instruction is generated.

```
{
    var a = _arg0;
    // closure
    var _tmp0 = new _plus();
    // application
    var _tmp1 = add;
    _tmp1._arg0 = a;
    // literal
    var _tmp2 = 2;
    // call
    var _tmp3 = _tmp1.run(_tmp2);
    // literal
    var _tmp4 = 1;
    // conditional
    if(!(_tmp3=_tmp4)){goto _skip0;}
    // literal
    "odd!" -> _tmp5;
    return _tmp5;
}
_skip0:
{
    var b = _arg0;
    ...
    return _tmp5;
}
_skip1:
```

See the figure 1 on the next page for an overview of instruction generation.

Main function

The main function is the entry point of the program. When the program is run, the main function is called, and prints its result to the console.

The body of the rule is generated like any rule in its own function. This improves readability by separating the main function specific code from the general rule code.

```
class _main{
    static <return type> _body(){
        <main rule>
    }
    static void Main(){
        <debugger initialization>
        System.Console.WriteLine(
            System.String.Format("{0}",
                                body()));
    }
}
```

figure 1: *an overview of instruction generation.*

instruction	MC	C#
literal	42 -> x	var x = 42;
conditional	x > 40	if(!(x>40)){goto skip0;}
deconstructor	lst -> x::xs	var _tmp0 = lst as _colon_colon; if(_tmp0==null){goto _skip0;} var x = _tmp0._arg0; var xs = _tmp0._arg1;
closure	(+) -> add	var add = new _plus();
application	add a -> inc	var inc = add; inc._arg0 = a;
call	inc b -> c	var c = inc.run(b);
.NET instr.	MC	C#
call	date.toString format -> str	var str = date.toString(format);
static call	System.DateTime.parse str -> date	var date = System.DateTime.parse(str);
get	date.DayOfWeek -> day	var day = date.DayOfWeek;
static get	date.DayOfWeek -> day	var day = date.DayOfWeek;
set	hr -> System.DateTime.hour	System.DateTime.hour = hr;
static set	hr -> System.DateTime.hour	System.DateTime.hour = hr;

Evolution

Before using inheritance, the plan was to use overlapping memory like C unions. Using `System.Runtime.InteropServices`, it was possible to set the specific offset of struct members. By overlapping fields in memory, we could achieve the same effect as C union. While this was multiplatform and worked well, it only worked with structs. This was a major limitation, because structs can only hold value-types. And the only value types are integers, floats, booleans and other structs.

have a fully-qualified name with type information, where as local identifiers only have the simple name.

C# identifiers

Since there are more valid MC identifier names than C# identifier names, some characters have to be escaped.

4.5 Mangler

The Mangler could be seen as part of the codegen, but the decisions are interesting enough to get its own research question.

How to generate the identifiers so they comply with the output language?

The mangler is responsible for generating a unique C# identifier for every instance of an MC identifier. The mangler is designed to be simple, and produce readable output. Readable output makes it easy to verify both the mangler and the generated code.

There are two kinds of identifier: global identifiers and local identifiers. Global identifiers

Valid C# identifiers must start with an alphabetic character or an underscore and the trailing characters must be alphanumeric or underscore⁷[10]. The only valid non-alphanumeric character is an underscore, so using it to escape with was a logical choice.

The first iteration of the code mangler just replaced all non-numeric characters with an underscore followed with the two-digit hexadecimal number. This generated correct identifiers but was very unreadable, `>>=` would translate to `_3E_3E_3D`. To remedy this, every ASCII symbol gets a readable label.

⁷regex: `[_A-Za-z][_A-Za-z0-9]*`

! _bang	- _dash	= _equal
# _hash	. _dot	? _quest
\$ _cash	/ _slash	@ _at
% _perc	\ _back	^ _caret
& _amp	: _colon	_ _under
' _prime	; _semi	` _tick
* _amp	< _less	_pipe
+ _plus	> _great	~ _tilde
, _comma		

Reserved words

C# allows reserved words to be used as valid identifiers if prefixed with an '@'[10].

Types

Global identifiers need type information embedded in the name since the name alone does uniquely identify it. Types can be recursive⁸, so the system for embedding types must be able to represent tree structures. We use the same syntax as the front-end but with `_S` as separator, `_L` for the left angle bracket and `_R` for the right angle bracket.

type	mangled
<code>array<int,3></code>	<code>array_Lint_S3_R</code>
<code>list<list<int>></code>	<code>list_Llist_Lint_R_R</code>

Evolution

The first iteration of the mangler just numbered every identifier. While this was a simple system to generate identifiers with, it was absolutely impossible to inspect the resulting code. Most of the mangler is the result of a desire for readable, inspectible output code.

4.6 Interpreter

The sixth research question lead to the implementation of an interpreter.

How to validate the code generator?

The interpreter was built to automatically validate the codegen and later allow constant-folding as an compiler optimization.

⁸see section 3.1

⁹see section 4.7

¹⁰see `interpreter.fs`

The automatic validation would be done by comparing the results of test programs between the interpreter and the compiler. If they mismatch, there is either a bug in the interpreter or more likely a bug in the codegen.

Evolution

The first design for an interpreter used the continuation monad. This is a complex construct that allows for arbitrary control flow.

The idea was that during debugging, you could change the line that was executed. It turned out that it was more desirable to have the debugger in the codegen instead of the interpreter⁹, so the primary benefit of the construct was lost.

The next design used explicit recursion to walk the list of instructions. This was a huge simplification compared to the continuation-monad, but every instruction still had to explicitly recurse. While all of the recursion were tail-calls, it still meant near-identical code duplication for each instruction.

Structure

The final design uses `fold`. This eliminated the recursion, making the `interpret` instruction a straight-line function that executed a single instruction. This interpreter was written under 100 lines¹⁰.

`fold` (or `reduce`) is a standard function in F# and other functional languages with the following type signature.

```
fold : (s->a->a) -> s -> [a] -> a
```

It applies a function for each element that takes the element and accumulator and produces a new accumulator. The first argument is that function, the second argument is the starting state and the last is the array. **[realworldhaskellch4]**.

example: `fold (+) 0 [1 2 3 4]` evaluates to 10 and `fold (*) 1 [1 2 3 4]` evaluates to 24.

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Using a fold radically simplifies the function, as all the explicit recursion becomes implicit. The function now only takes the state of the program and an instruction, and produces the new state of the program.

.NET instructions

The interpreter has to be able to load .NET libraries on the fly, since the libraries are not known at the time the compiler is compiled.

In the front-end interface, the `assemblies` field contains a list of strings. These strings are the assembly names the program is linked to. When a .NET function is called, the interpreter will open the assemblies one by one and search through it for a function that matches the name and signature of the one called. .NET datastructures and fields are handled the same way.

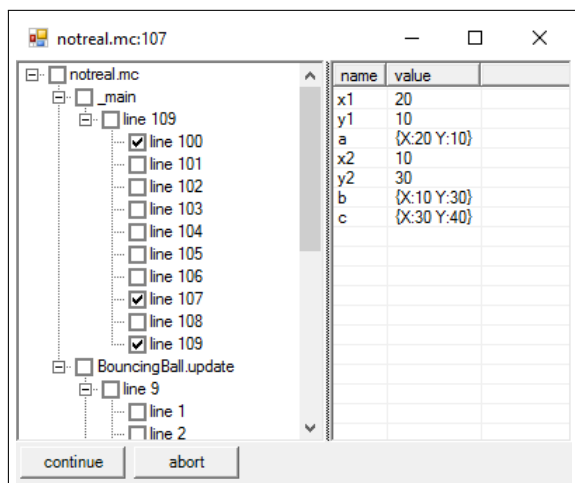
4.7 Debugger

The validation of the codegen lead to another validation-issue. If a test program is not behaving as expected, is there a bug in the test program or in the compiler?

In other words:

How to validate the test programs?

The answer to this is an embedded debugger in the target executable.



The program will then trigger a breakpoint on the first instruction and launch the debugger GUI. From the GUI, more breakpoints can be set with

the check-boxes. When the user presses 'continue' or 'abort', the gui will close and appear again on the next breakpoint.

The left pane shows a four level deep tree which sorts the program on file name, function name, rule and line.

The right pane shows a table with the name and value of the local identifiers defined up to the current breakpoint.

Program changes

When compiling with the debug flag set, some additions are made to target program.

Local identifier table After each instruction that defines named local identifiers, a new instruction is generated.

```
var foo = 42;
_DEBUG_symbol_table["foo"] = foo;
```

After each assignment to a named local identifier, the named identifier and the value are recorded in a key-value collection. This key-value collection will be passed to the debugger when a breakpoint is hit. A new key-value collection is defined at the start of each rule.

Break points When compiling with the debug-flag set, function closures will have a group of boolean arrays. One array for each rule in the function.

```
class <function name>{
  <arguments>
  static bool[] _DEBUG_breakpoints_0;
  static bool[] _DEBUG_breakpoints_1;
  <return value> _run(<last argument>){
    <body>
  }
}
```

The breakpoints are generated at each line of sourcecode in the rule. This is different than breaking at every instruction, as normalization often splits single lines into multiple instructions.

```
...
if(_DEBUG_Breakpoints_1[6]){
    _DEBUG.breakpoint("filename.mc", 12,
        _DEBUG_symbol_table);
}
...
```

Debug class

The breakpoint function is defined as a public static member of the debug class.

The debugger is defined in a separate file, `_DEBUG.cs`, which is imported by the target executable. This is done to keep the program-specific code out of `_DEBUG.cs`.

`_DEBUG.cs` contains the class `_DEBUG`. This class contains only the following public static items.

1. the program tree
2. the breakpoint tree
3. the breakpoint function

The program builds up the program tree and the breakpoint tree in the main function, before the first user-written line starts. The trees are both four-levels deep and sorted on filename, function name, rule and linenummer. The breakpoint function is called when the program hits a breakpoint.

This was chosen because breakpoint checks happen every few instructions, so they have a huge effect on debug performance. Straight arrays with booleans are very fast to index since it only costs one bounds-check, one addition and one dereference.

The tree representation of the program is four levels deep. The first level represents the file, the second level represents the function, the third level represents the rule and the fourth level represents the premise. This tree representation is initialized in the main function, before the user code begins.

The breakpoint table Breakpoints are realised as an array of booleans for each rule in a closure. The class also contains a `bool[][][]`

The breakpoint function This class contains a static method `breakpoint` that will pause the execution of the program and present the GUI. When the user presses 'continue' or 'abort', the GUI will close and the breakpoint method will return control back to the program.

The first two arguments to `_DEBUG.breakpoint` are the filename and the linenummer. This is to uniquely identify the callsite. The third argument is the symboltable that has been accumulated so far.

Evolution

First own tree impl. Then 4d node. Now winform tree nodes.

5 Results

After answering all the subquestions, one thing is left: proving the main research question. The main research question and its requirements were:

How to implement a transformation from type-checked Meta-Casanova(MC) to executable code within the timeframe of the internship?

Where the transformation must satisfy these requirements:

1. The backend must in no case produce an incorrect program.
2. The executable must be able to interoperate with .NET.
3. The generated code must run on all the platforms .NET runs on.
4. The performance of the generated program should be comparable to Python.

In order to satisfy these requirements, test programs are needed.

5.1 Test programs

Unfortunately, since the front-end was incomplete, it is not possible to compile source files. It *is* however possible to write the front-end interface by hand.

Data test

The first test was developed to test the Data declarations. It is equivalent to the following mc code.

```
Data int -> ":" -> List -> List
Data "nil" -> List

-----
main -> 0
```

```
20.0 -> x1
10.0 -> y1
Microsoft.Xna.Framework.Vector2 x1 y1 -> a
20.0 -> x2
10.0 -> y2
Microsoft.Xna.Framework.Vector2 x2 y2 -> b
Microsoft.Xna.Framework.Vector2.+ a b -> c
Microsoft.Xna.Framework.Vector2.Normalize c
y2 -> v.x
v.x -> ret

-----
run -> ret
```

Which returns 20. This is especially interesting to debug, because we can see the values change.

List length test

The list length program defined a list datastructure and a program to compute its length. This was used since it uses each basic instruction at least once, as well as matching. It is equivalent to the following MC code:

```
Data int -> ":" -> List -> List
Data "nil" -> List

Func "length" -> List -> int

-----
length nil -> 0

lengtht xs -> res
-----
length x::xs -> res+1

-----
main -> length (1::2::3::4::nil)
```

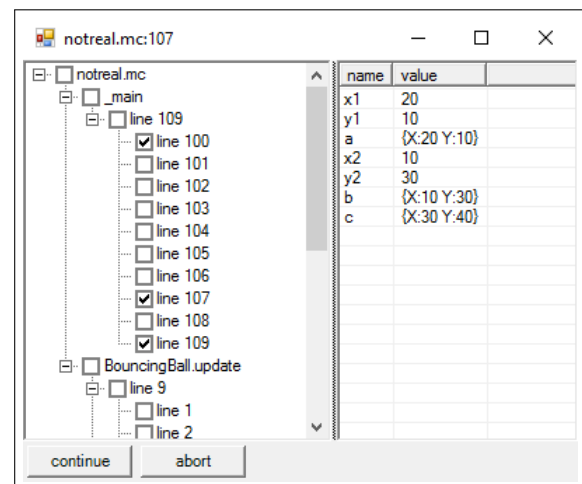
Which when executed prints the following on screen.

4

This program can also be debugged with the embedded debugger.

XNA test

The second test program was to test the .Net functionality. It consists of a simple program that modifies XNA datastructures, specifically the Vector2.



5.2 Verification

This section will go over each requirement and — show that requirements are met —

6 Conclusions

The result is a working, reliable, performant back-end, with interpreter, validator and embedded debugger. All finished within the timeframe of the internship.

To prove it works, three test programs were written. All are correctly generated, all run in the interpreter, and all can be debugged.

7 Recommendations

The back-end is in a functional state, but it could use more features. Most of the features are op-

timizations. Optimizations generally have a relatively small effect, but often take up a lot of development time.

Inlining

The most important optimization is inlining[inlining]. Inlining is the process of replacing a function call with the function body. While this saves a function call, the greatest benefit is that it enables other optimizations.

When the function body is copied in the larger context of the callsite, some input values may be identified as compile-time constants, enabling a whole array of optimizations.

Inlining is not always desirable. If a large function is called from many different places, the size of the program increases, increasing the cache-misses on the instruction cache, reducing performance.

The choice for inlining a call should consider:

1. If the function recurses in any way, even indirect recursion. This makes inlining impossible.
2. The size of the function. The smaller the function, the greater the inlining benefit.
3. The amount of times the function is called. If the function is only called once, inlining has no disadvantages. For each additional time, the size of the program increases.

Tail call optimization

— use `gotos` —

Constant folding

— C# does this a bit (see <http://stackoverflow.com/a/5669035>) —

8 Reflection

It went well. — show that dublin descriptors are met —

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B Glossary

polymorphic can have multiple types

boilerplate code expl

C Source

C.1 Common.fs

```

1  module Common
2
3  type Position = { File : string; Line : int; Col : int }
4      with
5      member pos.NextLine = { pos with Line = pos.Line + 1; Col = 1 }
6      member pos.NextChar = { pos with Col = pos.Col + 1 }
7      static member FromPath(path:string) = { File = path; Line = 1; Col = 1 }
8      static member Zero = { File = ""; Line = 1; Col = 1 }
9
10 type Bracket = Curly | Round | Square | Lambda | Implicit | Comment
11
12 type Predicate = Less | LessEqual | Equal | GreaterEqual | Greater | NotEqual
13
14 type genericId<'a>= {Namespace:List<string>;Name:'a;}
15 type Id          = genericId<string>
16
17 type Literal = I64 of System.Int64
18               | U64 of System.UInt64
19               | I32 of System.Int32
20               | U32 of System.UInt32
21               | F64 of System.Double
22               | F32 of System.Single
23               | String of System.String
24               | Bool of System.Boolean
25               | Void

```

C.2 CodegenInterface.fs

```

1  module CodegenInterface
2  open Common
3
4  type LambdaId = genericId<int>
5  type TypeId   = genericId<string>
6
7  type Type = DotNetType of TypeId
8               | McType of TypeId
9               | TypeApplication of Type*List<Type>
10              | Arrow of Type*Type
11
12 type local_id = Named of string
13               | Tmp of int
14
15 type premisses = Literal of LiteralAssignment // assign literal to local
16               | Conditional of Conditional // stops evaluation if condition
17               | is false
18               | Destructor of Destructor // destructs Mc data into its
19               | constructor arguments
20               | ConstructorClosure of closure<Id> // assigns mc data constructor
21               | closure to local
22               | FuncClosure of closure<Id> // assigns mc func closure to
23               | local
24               | LambdaClosure of closure<LambdaId> // assigns lambda closure to local
25               | Application of Application // applies an argument to a local
26               | closure
27               | ApplicationCall of ApplicationCall // applies an argument to a local
28               | closure and calls it
29               | DotNetCall of DotNetCall // calls .Net method and assigns
30               | result to local
31               | DotNetStaticCall of DotNetStaticCall // calls .Net static method and
32               | assigns result to local

```

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```
25 | DotNetConstructor of DotNetStaticCall // calls .Net constructor
26 | DotNetGet of DotNetGet // gets field and assigns it to
    local
27 | DotNetSet of DotNetSet // sets field from local
28 and LiteralAssignment = {value:Literal; dest:local_id}
29 and Conditional = {left:local_id; predicate:Predicate; right:local_id}
30 and Destructor = {source:local_id; destructor:Id; args:List<local_id>}
31 and closure<'a> = {func:'a;dest:local_id}
32 and Application = {closure:local_id; argument:local_id; dest:local_id}
33 and ApplicationCall = {closure:local_id; argument:local_id; dest:local_id; side_effect:
    bool}
34 and DotNetStaticCall = {func: Id; args:List<local_id>; dest:local_id; side_effect:bool}
35 and DotNetCall = {instance: local_id; func: string; args:List<local_id>; dest:
    local_id; side_effect:bool; mutates_instance:bool}
36 and DotNetGet = {instance: local_id; field: string; dest:local_id}
37 and DotNetSet = {instance: local_id; field: string; src:local_id}
38
39 type rule = {
40   side_effect :bool
41   input :List<local_id>
42   output :local_id
43   premis :List<premise*int> // linenumber
44   typemap:Map<local_id,Type>
45   definition: Position
46 }
47
48 type data = {
49   args :List<Type>
50   outputType :Type
51 }
52
53 type CompilerFlags = {debug:bool}
54
55 type fromTypecheckerWithLove = {
56   assemblies : List<string>
57   funcs : Map<Id,List<rule>*Position>
58   lambdas : Map<LambdaId,rule>
59   datas : List<Id*data>
60   main : rule
61   flags : CompilerFlags
62 }
63
64 let (-->) t1 t2 =
65   Arrow(t1,t2)
66
67 let mutable tmp_index = 0
68
69 let next_tmp () =
70   let current = tmp_index
71   tmp_index <- tmp_index+1
72   Tmp(current)
73
74 let current_tmp () =
75   Tmp(tmp_index-1)
76
77 let reset_tmp () =
78   do tmp_index <- 1
79   Tmp(0)
80
81 let reset () =
82   do tmp_index <- 0
```

C.3 Interpreter.fs

```
1 module Interpreter
2 open Common
3 open CodegenInterface
```

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```
4 open ParserMonad
5
6 let print_loc (x:local_id) = match x with Named x -> x | Tmp x -> sprintf "%d" x
7 let print_id (x:Id) = x.Namespace @ [x.Name] |> String.concat "."
8
9 let print_premisse (p:premise,i:int) :string =
10   let print_lamb (x:LambdaId) = x.Namespace @ [sprintf "lambda%d" x.Name] |> String.concat
    "."
11   match p with
12   | Literal          x -> sprintf "%03d:_%LITR_%s_%s->_%s" i x.value (print_loc x.dest)
13   | Conditional      x -> sprintf "%03d:_%COND_%s_%sA_%s" i (print_loc x.left) x.predicate
    (print_loc x.right)
14   | Destructor       x -> sprintf "%03d:_%DTOR_%s_%s_%s->_%s" i (print_id x.destructor) (
    print_loc x.source) (x.args|>List.map print_loc|>String.concat "_")
15   | ConstructorClosure x -> sprintf "%03d:_%CTOR_%s_%s->_%s" i (print_id x.func) (print_loc x
    .dest)
16   | FuncClosure      x -> sprintf "%03d:_%FUNC_%s_%s->_%s" i (print_id x.func) (print_loc x
    .dest)
17   | LambdaClosure    x -> sprintf "%03d:_%LAMB_%s_%s->_%s" i (print_lamb x.func) (print_loc
    x.dest)
18   | Application      x -> sprintf "%03d:_%APPL_%s_%s_%s->_%s" i (print_loc x.closure) (
    print_loc x.argument) (print_loc x.dest)
19   | ApplicationCall   x -> sprintf "%03d:_%CALL_%s_%s_%s->_%s_%s" i (print_loc x.closure) (
    print_loc x.argument) (print_loc x.dest) (if x.side_effect then "{SIDE-EFFECT}" else "
    ")
20   | DotNetConstructor x -> sprintf "%03d:_%NCON_%s(%s)_->_%s_%s" i (print_id x.func) (x.
    args|>List.map print_loc|>String.concat "_") (print_loc x.dest)(if x.side_effect then
    "{SIDE-EFFECT}" else "")
21   | DotNetStaticCall  x -> sprintf "%03d:_%NSCA_%s(%s)_->_%s_%s" i (print_id x.func) (x.
    args|>List.map print_loc|>String.concat "_") (print_loc x.dest) (if x.side_effect then
    "{SIDE-EFFECT}" else "")
22   | DotNetCall        x -> sprintf "%03d:_%NDCA_%s.%s(%s)_->_%s_%s_%s" i (print_loc x.
    instance) x.func (x.args|>List.map print_loc|>String.concat "_") (print_loc x.dest) (
    if x.side_effect then "{SIDE-EFFECT}" else "") (if x.mutates_instance then "{MUTATES-
    INSTANCE}" else "")
23   | DotNetGet         x -> sprintf "%03d:_%NGET_%s.%s_%s->_%s" i (print_loc x.instance) x.
    field (print_loc x.dest)
24   | DotNetSet         x -> sprintf "%03d:_%NSET_%s.%s_%s<-_%s" i (print_loc x.instance) x.
    field (print_loc x.src)
25
26 type global_context = {assemblies:List<System.Reflection.Assembly>;funcs:Map<Id,List<rule
    >*Position>;lambdas:Map<LambdaId,rule>;datas:List<Id*data>;main:rule;}
27
28 let getClass (assemblies) (name:string) :System.Type =
29   let ts =
30     assemblies |> List.fold (fun (a:List<System.Type>) (v:System.Reflection.Assembly)->
31       let t:System.Type = v.GetType(name,false)
32       if t=null then a else t::a
33     ) []
34   match ts with
35   | [t] -> t
36   | [] -> failwith ("EVAL_ERROR:_" + name + "_not_found_in_assembly")
37   | _ -> failwith ("EVAL_ERROR:_" + name + "_found_in_multiple_assemblies")
38
39 let staticCallNonBuiltin (x:DotNetStaticCall) (symbol_table:Map<local_id,obj>) (assemblies
    :list<System.Reflection.Assembly>) :obj =
40   let t = getClass assemblies (x.func.Namespace|>String.concat ".")
41   let args = x.args |> List.map (fun a->symbol_table.[a]) |> List.toArray
42   let argtypes = System.Type.GetTypeArray(args)
43   let f = t.GetMethod(x.func.Name,argtypes)
44   f.Invoke(null,args)
45
46 let DotNetConstruct (x:DotNetStaticCall) (symbol_table:Map<local_id,obj>) (assemblies:list
    <System.Reflection.Assembly>) :obj =
47   let t = getClass assemblies (x.func.Namespace@[x.func.Name]|>String.concat ".")
48   let args = x.args |> List.map (fun a->symbol_table.[a]) |> List.toArray
49   let argtypes = System.Type.GetTypeArray(args)
```

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```
50   let c = t.GetConstructor(argtypes)
51   c.Invoke(args)
52
53   let dynamicCallNonBuiltin (x:DotNetCall) (parent_type:Id) (symbol_table:Map<local_id,obj>)
54     (assemblies:list<System.Reflection.Assembly>) :obj =
55     let t = getClass assemblies (parent_type.Namespace@[parent_type.Name]>String.concat ".")
56     let args = x.args |> List.map (fun a->symbol_table.[a]) |> List.toArray
57     let argtypes = System.Type.GetTypeArray(args)
58     let f = t.GetMethod(x.func,argtypes)
59     f.Invoke(symbol_table.[x.instance],args)
60
61   let dotNetGet (x:DotNetGet) (parent_type:Id) (symbol_table:Map<local_id,obj>) (assemblies:
62     list<System.Reflection.Assembly>) :obj =
63     let t = getClass assemblies (parent_type.Namespace@[parent_type.Name]>String.concat ".")
64     let field = t.GetField(x.field)
65     field.GetValue(symbol_table.[x.instance])
66
67   let dotNetSet (x:DotNetSet) (parent_type:Id) (symbol_table:Map<local_id,obj>) (assemblies:
68     list<System.Reflection.Assembly>) =
69     let t = getClass assemblies (parent_type.Namespace@[parent_type.Name]>String.concat ".")
70     let field = t.GetField(x.field)
71     field.SetValue(symbol_table.[x.instance],symbol_table.[x.src])
72
73   let rec eval_step (p:premise,i:int)
74     (global_context:global_context)
75     (type_map:Map<local_id,Type>)
76     (symbol_table:Map<local_id,obj>)
77     :List<Map<local_id,obj>> =
78   (*
79   do symbol_table |> Map.toSeq |> Seq.iter (fun(id,o)->
80     do System.Console.ForegroundColor <- System.ConsoleColor.Magenta
81     do printf "%s\n" (print_loc id)
82     do System.Console.ResetColor()
83     do printf "%A\n" o
84     ()
85   *)
86   do System.Console.ForegroundColor <- System.ConsoleColor.Yellow
87   do printf "%s\n" (print_premise (p,i))
88   do System.Console.ResetColor()
89   match p with
90   | Literal x ->
91     let value = match x.value with
92       | I64 x->box x | U64 x->box x | F64 x->box x
93       | I32 x->box x | U32 x->box x | F32 x->box x
94       | String x->box x | Bool x->box x | Void->box()
95     [symbol_table.Add(x.dest,value)]
96   | Conditional x ->
97     let l = symbol_table.[x.left] :?> System.IComparable
98     let r = symbol_table.[x.right] :?> System.IComparable
99     let f = match x.predicate with Less -> (<) | LessEqual->(<=) | Equal -> (=) |
100       GreaterEqual -> (>=) | Greater -> (>) | NotEqual -> (<>)
101     if f l r then [symbol_table.[x.dest]] else []
102   | Destructor x ->
103     let id,args = symbol_table.[x.source] :?> Id*List<obj>
104     if x.destructor = id then
105       let additions = args |> List.zip x.args |> Map.ofList
106       [symbol_table |> Map.fold (fun a k v->a|>Map.add k v) additions]
107     else
108       []
109   | FuncClosure x
110   | ConstructorClosure x ->
111     let ret = x.func,List.empty
112     [symbol_table.Add(x.dest,(box ret))]
```

```

110 | LambdaClosure x ->
111   let ret = x.func,List.empty
112   [symbol_table.Add(x.dest,(box ret))]
113 | Application x ->
114   match symbol_table.[x.closure] with
115   | :? (Id*List<obj>) as foo ->
116     let id,args = foo
117     let res = id,(args@[symbol_table.[x.argument]])
118     [symbol_table.Add(x.dest,(box res))]
119   | :? (LambdaId*List<obj>) as foo ->
120     let id,args = foo
121     let res = id,(args@[symbol_table.[x.argument]])
122     [symbol_table.Add(x.dest,(box res))]
123 | ApplicationCall x ->
124   match symbol_table.[x.closure] with
125   | :? (Id*List<obj>) as foo ->
126     let id,args = foo
127     let filled_args = args@[symbol_table.[x.argument]]
128     match global_context.datas |> List.tryFind (fun(x,->x=id) with
129     | Some(id,data) ->
130       [symbol_table.Add(x.dest,box filled_args)]
131     | None ->
132       fst global_context.funcs.[id] |> List.map (fun rule -> // for each rule
133         let results = eval_rule rule global_context filled_args
134         results |> List.map (fun v->symbol_table.Add(x.dest,v))
135       )|>List.concat
136   | :? (LambdaId*List<obj>) as foo ->
137     let id,args = foo
138     let filled_args = args@[symbol_table.[x.argument]]
139     let rule = global_context.lambdas.[id]
140     let results = eval_rule rule global_context filled_args
141     results |> List.map (fun v->symbol_table.Add(x.dest,v))
142 | DotNetStaticCall x ->
143   let ret:obj =
144     match x.func.Namespace with
145     | ["System";"Int32"] when x.args.Length=2 ->
146       let l = symbol_table.[x.args.[0]] :?> System.Int32
147       let r = symbol_table.[x.args.[1]] :?> System.Int32
148       match x.func.Name with "+"->box(l+r) | "/"->box(l/r) | "*"->box(l*r) | "%"->box(l%
149 r) | "-">box(l-r) | _ ->staticCallNonBuiltin x symbol_table global_context.assemblies
150 | ["System";"Int64"] when x.args.Length=2 ->
151   let l = symbol_table.[x.args.[0]] :?> System.Int64
152   let r = symbol_table.[x.args.[1]] :?> System.Int64
153   match x.func.Name with "+"->box(l+r) | "/"->box(l/r) | "*"->box(l*r) | "%"->box(l%
154 r) | "-">box(l-r) | _ ->staticCallNonBuiltin x symbol_table global_context.assemblies
155 | ["System";"Single"] when x.args.Length=2 ->
156   let l = symbol_table.[x.args.[0]] :?> System.Single
157   let r = symbol_table.[x.args.[1]] :?> System.Single
158   match x.func.Name with "+"->box(l+r) | "/"->box(l/r) | "*"->box(l*r) | "%"->box(l%
159 r) | "-">box(l-r) | _ ->staticCallNonBuiltin x symbol_table global_context.assemblies
160 | ["System";"Double"] when x.args.Length=2 ->
161   let l = symbol_table.[x.args.[0]] :?> System.Double
162   let r = symbol_table.[x.args.[1]] :?> System.Double
163   match x.func.Name with "+"->box(l+r) | "/"->box(l/r) | "*"->box(l*r) | "%"->box(l%
164 r) | "-">box(l-r) | _ ->staticCallNonBuiltin x symbol_table global_context.assemblies
165 | _ -> staticCallNonBuiltin x symbol_table global_context.assemblies
166 [symbol_table.Add(x.dest,ret)]
167 | DotNetConstructor x ->
168   let ret = DotNetConstruct x symbol_table global_context.assemblies
169   [symbol_table.Add(x.dest,ret)]
170 | DotNetCall x ->
171   match type_map.[x.instance] with
172   | DotNetType t ->
173     let ret = dynamicCallNonBuiltin x t symbol_table global_context.assemblies
174     [symbol_table.Add(x.dest,ret)]
175 | DotNetGet x ->
176   match type_map.[x.instance] with

```

```

173 | DotNetType t ->
174 | let ret = dotNetGet x t symbol_table global_context.assemblies
175 | [symbol_table.Add(x.dest,ret)]
176 | DotNetSet x ->
177 | match type_map.[x.instance] with
178 | | DotNetType t ->
179 | | do dotNetSet x t symbol_table global_context.assemblies
180 | | [symbol_table]
181
182 and eval_rule (rule:rule)
183 | (ctxt:global_context)
184 | (args:List<obj>) :List<obj> =
185 | let input = Seq.zip rule.input args |> Map.ofSeq
186 | let called_stabs = ([input],rule.premis) |> List.fold (fun (stabs:List<Map<local_id,
187 | obj>>) p -> // for each instruction
188 | stabs |> List.map (fun stab -> // for each fork
189 | eval_step p ctxt rule.typemap stab
190 | ) |> List.concat
191 | )
192 | let output = called_stabs |> List.map (fun stab-> stab.[rule.output])
193 | output
194
195 let load_assemblies (src:List<string>) :List<System.Reflection.Assembly> =
196 | src |> List.map (fun str-> System.Reflection.Assembly.LoadFrom(str) )
197
198 let eval_main (src:fromTypecheckerWithLove) =
199 | let ctxt:global_context={assemblies=load_assemblies src.assemblies;funcs=src.funcs;datas
200 | =src.datas;lambdas=src.lambdas;main=src.main}
201 | do printf "starting interpretation\n"
202 | let res = eval_rule ctxt.main ctxt []
203 | do printf "results:\n%s" (res|>List.map (sprintf "%A\n")|>String.concat "")
204 | res

```

C.4 Codegen.fs

```

1 module Codegen
2 open Common
3 open CodegenInterface
4 open Mangle
5
6 let mutable flags:CompilerFlags={debug=false};
7
8 let fst(x,_)=x
9 let snd(_,x)=x
10
11 let foldi (f:int->'state->'element->'state) (s:'state) (lst:seq<'element>) :'state =
12 | let fn ((counter:int),(state:'state)) (element:'element) :int*'state =
13 | counter+1,(f counter state element)
14 | let _,ret = lst|>Seq.fold fn (0,s)
15 | ret
16
17 let ice () =
18 | do System.Console.BackgroundColor <- System.ConsoleColor.Red
19 | do System.Console.Write "INTERNAL_COMPILER_ERROR"
20 | do System.Console.ResetColor()
21
22 type NamespacedItem = Ns of string*List<NamespacedItem>
23 | Data of string*data
24 | Function of string*List<rule>
25 | Lambda of int*rule
26
27 let construct_tree (input:fromTypecheckerWithLove) :List<NamespacedItem> =
28 | let rec datatree (s:List<NamespacedItem>) (idx:List<string>,v:string*data) :List<
29 | NamespacedItem> =
30 | match idx with
31 | | [] -> (Data(v))::s

```



```

31 | n::ns -> match s |> List.partition (fun x->match x with Ns(n,_)->true | _->false)
    with
32 | [Ns(n,body)],rest -> Ns(n,datatree body (ns,v))::rest
33 | [],list -> Ns(n,datatree [] (ns,v))::list
34 let rec funtree (s:List<NamespacedItem>) (idx:List<string>,v:string*(List<rule>*>
    Position)) :List<NamespacedItem> =
35 match idx with
36 | [] -> let (l,(r,_)) = v in (Function(l,r))::s
37 | n::ns -> match s |> List.partition (fun x->match x with Ns(n,_)->true | _->false)
    with
38 | [Ns(n,body)],rest -> Ns(n,functree body (ns,v))::rest
39 | [],list -> Ns(n,functree [] (ns,v))::list
40 let rec lambdatree (s:List<NamespacedItem>) (idx:List<string>,v:int*rule) :List<
    NamespacedItem> =
41 match idx with
42 | [] -> (Lambda(v))::s
43 | n::ns -> match s |> List.partition (fun x->match x with Ns(n,_)->true | _->false)
    with
44 | [Ns(n,body)],rest -> Ns(n,lambdatree body (ns,v))::rest
45 | [],list -> Ns(n,lambdatree [] (ns,v))::list
46 let go input output state = input |> Seq.map (fun (n,d)->(List.rev n.Namespace),(n.Name,
    d)) |> Seq.fold output state
47 [] |> go (Map.toSeq input.lambdas) lambdatree
48 |> go (Map.toSeq input.funcs) functree
49 |> go input.datas datatree
50
51 let print_literal (lit:Literal) =
52 match lit with
53 | I64 i -> sprintf "%dL" i
54 | U64 i -> sprintf "%uUL" i
55 | I32 i -> sprintf "%u" i
56 | U32 i -> sprintf "%uU" i
57 | F64 i -> sprintf "%f" i
58 | F32 i -> sprintf "%ff" i
59 | String s -> sprintf "%s" s
60 | Bool b -> if b then "true" else "false"
61 | Void -> "void"
62
63 let print_predicate (p:Predicate) :string=
64 match p with Less -> "<" | LessEqual -> "<=" | Equal -> "=" | GreaterEqual -> ">=" |
    Greater -> ">" | NotEqual -> "!="
65
66 let field (n:int) (t:Type) :string =
67 sprintf "public_%s_arg%d;\n" (mangle_type t) n
68
69 let highest_tmp (typemap:Map<local_id,Type>): int =
70 typemap |> Map.fold (fun s k _ -> match k with Tmp(x) when x>s -> x | _ -> s) 0
71
72 let get_map (a:local_id) (m:Map<local_id,int>) :int*Map<local_id,int> =
73 match Map.tryFind a m with None -> 0,(Map.add a 1 m) | Some x -> x,(Map.add a (x+1) m)
74
75 let overloadableOps:Map<string,string> =
76 [
77 "op_Equality","=="
78 "op_Inequality","!="
79 "op_GreaterThan",">"
80 "op_LessThan","<"
81 "op_GreaterThanOrEqual",">="
82 "op_LessThanOrEqual","<="
83 "op_BitwiseAnd","&"
84 "op_BitwiseOr","|"
85 "op_Addition","+"
86 "op_Subtraction","-"
87 "op_Division","/"
88 "op_Modulus","%"
89 "op_Multiply","*"
90 "op_LeftShift","<<"

```

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```
91     "op_RightShift", ">"
92     "op_ExclusiveOr", "^"
93     "op_UnaryNegation", "-"
94     "op_UnaryPlus", "+"
95     "op_LogicalNot", "!"
96     "op_OnesComplement", "~"
97     "op_False", "false"
98     "op_True", "true"
99     "op_Increment", "++"
100    "op_Decrement", "--"
101  ] |> Map.ofList
102
103  let print_label (i:int) = sprintf "_skip%d" i
104
105  let print_debug_tree (fromTypeChecker:Map<Id,list<rule>*Position>) (main:rule) =
106    let tree =
107      // first flatten the hierarchy
108      let rules = fromTypeChecker |> Map.toSeq |> Seq.map (fun(name,(lst,pos))->lst|>Seq.
ofList|>Seq.map(fun rule->name,rule,pos)) |> Seq.concat
109      // add main to the flat list
110      let rules = rules |> Seq.append ([{Namespace=[];Name="main"},main,main.definition])
111      // then group by file (that the rule is defined by)
112      let files = rules |> Seq.groupBy (fun(id,rule,pos)->rule.definition.File)
113      // within each file, group by func (and strip info out of rule)
114      files |> Seq.map (fun(filename,rules)->
115        let funcs = rules |> Seq.groupBy (fun(id,rule,pos)->id,pos)
116        |> Seq.map (fun((id,pos),rules)->id,pos,rules|>Seq.map(fun(id,rule,pos)
->rule))
117        filename,funcs)
118    let debug_tree =
119      let per_file = tree |> Seq.mapi (fun filenr (filename,funcs)->
120        let per_func = funcs |> Seq.mapi (fun funcnr (funcname,declposition,rules)->
121          let per_rule = rules |> Seq.mapi (fun rulenn (rule) ->
122            let per_line = rule.premis |> Seq.groupBy snd
123            let per_prem = (per_line(*|>Seq.rev|>Seq.tail|>Seq.rev*)) |> Seq.mapi (fun
premnr (linenumber,prems)->
124              sprintf "_DEBUG.program_tree.Nodes[%d].Nodes[%d].Nodes[%d].Nodes.Add(\"line_%d
\");\n" filenr funcnr rulenn linenumber )
125              sprintf "_DEBUG.program_tree.Nodes[%d].Nodes[%d].Nodes.Add(\"line_%d\");\n"
filenr funcnr (Seq.last per_line|>fst)
126              + (String.concat "" per_prem) )
127              sprintf "_DEBUG.program_tree.Nodes[%d].Nodes.Add(\"%s\");\n" filenr (mangle_id
funcname)
128              + (String.concat "" per_rule) )
129              sprintf "_DEBUG.program_tree.Nodes.Add(\"%s\");\n" filename
130              + (String.concat "" per_func) )
131            per_file |> String.concat ""
132        let breakpoint_tree =
133          let per_file = tree |> Seq.map (fun(_,funcs)->
134            let per_func = funcs |> Seq.map (fun(id,_,rules)->
135              let per_rule = rules |> Seq.mapi (fun i _ ->
136                sprintf "%s._DEBUG.breakpoints_%d" (mangle_id id) i)
137                sprintf "new_bool[][][%s]" (String.concat "," per_rule) )
138                sprintf "new_bool[][][%s]{\n%s\n}" (String.concat "," per_func) )
139                sprintf "new_bool[][][%s]{\n%s\n}" (String.concat "," per_file)
140              ("_DEBUG.breakpoints="+breakpoint_tree)+debug_tree
141          )
142        let premiss (p:premiss) (m:Map<local_id,Type>) (app:Map<local_id,int>) (rule_nr:int) =
143          match p with
144          | Literal x -> app,sprintf "/*LITR*/var_%s_=%s;\n"
(mangle_local_id x.dest)
145            (print_literal x.value)
146          | Conditional x -> app,sprintf "/*COND*/if(!(%s_%s_%s)){goto_%s;}\n"
(mangle_local_id x.left)
147            (print_predicate x.predicate)
148            (mangle_local_id x.right)
149            (print_label rule_nr)
```

```

152 | Destructor x ->
153 |   let new_id = (Tmp(1+(highest_tmp m)))
154 |   app,sprintf "/*DTOR*/var_%s=%s; \nif(%s==null){goto_%s;}\n%s"
155 |     (mangle_local_id new_id)
156 |     (mangle_local_id x.source)
157 |     (mangle_id x.destructor)
158 |     (mangle_local_id new_id)
159 |     (print_label rule_nr)
160 |     (x.args|>List.mapi(fun nr arg->sprintf "var_%s=%s._arg%d;\n" (mangle_local_id arg) (
161 |       mangle_local_id new_id) nr)|>String.concat "")
162 | ConstructorClosure x -> (app|>Map.add x.dest 0),sprintf "/*FUNC*/var_%s=%s; \n"
163 |   (mangle_local_id x.dest)
164 |   (mangle_id x.func)
165 | LambdaClosure x -> (app|>Map.add x.dest 0),sprintf "/*LAMB*/var_%s=%s; \n"
166 |   (mangle_local_id x.dest)
167 |   (mangle_lambda x.func)
168 | DotNetCall x ->
169 |   let isVoid = m.[x.dest]=Type.DotNetType({Namespace=[];Name="void"})
170 |   app,sprintf "/*NDCA*/%s%s(%s);\n"
171 |     (if isVoid then "" else sprintf "var_%s=%s" (mangle_local_id x.dest))
172 |     (mangle_local_id x.instance)
173 |     x.func
174 |     (x.args |> List.map mangle_local_id|>String.concat ",")
175 | DotNetStaticCall x ->
176 |   let isVoid = m.[x.dest]=Type.DotNetType({Namespace=[];Name="void"})
177 |   if overloadableOps.ContainsKey(x.func.Name) then
178 |     let args = x.args |> List.rev
179 |     app,sprintf "/*NSCA*/%s%s(%s);\n"
180 |       (if isVoid then "" else sprintf "var_%s=%s" (mangle_local_id x.dest))
181 |       (match x.args.Length with
182 |       | 1 -> ""
183 |       | 2 -> mangle_local_id args.[1])
184 |       overloadableOps.[x.func.Name]
185 |       (mangle_local_id args.[0])
186 |   else
187 |     app,sprintf "/*NSCA*/%s%s(%s);\n"
188 |       (if isVoid then "" else sprintf "var_%s=%s" (mangle_local_id x.dest))
189 |       (x.func.Namespace@[x.func.Name]|>String.concat ".")
190 |       (x.args |> List.map mangle_local_id|>String.concat ",")
191 | DotNetConstructor x -> app,sprintf "/*NCON*/var_%s=%s; \n"
192 |   (mangle_local_id x.dest)
193 |   (x.func.Namespace@[x.func.Name]|>String.concat ".")
194 |   (x.args |> List.map mangle_local_id|>String.concat ",")
195 | DotNetGet x -> app,sprintf "/*NGET*/var_%s=%s; \n"
196 |   (mangle_local_id x.dest)
197 |   (mangle_local_id x.instance)
198 |   x.field
199 | DotNetSet x -> app,sprintf "/*NSET*/%s.%s=%s; \n"
200 |   (mangle_local_id x.instance)
201 |   x.field
202 |   (mangle_local_id x.src)
203 | Application x ->
204 |   let i = match app|>Map.tryFind x.closure with Some(x)->x | None-> failwith (sprintf "
205 |     Application failed:_%s is not a closure." (mangle_local_id x.closure))
206 |   (app|>Map.add x.dest (i+1)),sprintf "/*APPL*/var_%s=%s; %s.%s=%s; \n"
207 |     (mangle_local_id x.dest)
208 |     (mangle_local_id x.closure)
209 |     (mangle_local_id x.dest)
210 |     (sprintf "_arg%d" i)
211 |     (mangle_local_id x.argument)
212 | ApplicationCall x ->
213 |   let i = match app|>Map.tryFind x.closure with Some(x)->x | None-> failwith (sprintf "
214 |     ApplicationCall failed:_%s is not a closure." (mangle_local_id x.closure))
215 |   (app|>Map.add x.dest (i+1)),sprintf "/*CALL*/%s.%s=%s; %s.run(); \n"
216 |     (mangle_local_id x.closure)
217 |     (sprintf "_arg%d" i)

```

```

216         (mangle_local_id x.argument)
217         (mangle_local_id x.dest)
218         (mangle_local_id x.closure)
219
220 let get_definitions (p:premise) :List<local_id> =
221     match p with
222     | Literal          x -> [x.dest]
223     | Conditional      _ -> []
224     | Destructor       x -> x.args
225     | ConstructorClosure x -> [x.dest]
226     | FuncClosure      x -> [x.dest]
227     | LambdaClosure    x -> [x.dest]
228     | Application      x -> [x.dest]
229     | ApplicationCall  x -> [x.dest]
230     | DotNetCall       x -> [x.dest]
231     | DotNetStaticCall x -> [x.dest]
232     | DotNetConstructor x -> [x.dest]
233     | DotNetGet        x -> [x.dest]
234     | DotNetSet        x -> [x.src]
235
236 let print_rule (rule_nr:int) (rule:rule) =
237     let symbol_table_add id =
238         let s=mangle_local_id id
239         if id=Named("nil") then "" else sprintf "_DEBUG_symbol_table[%s]=%s;\n" s s
240     let linegroups:seq<int*seq<premise>> =
241         rule.premis |> Seq.groupBy (fun (_,x)->x) |> Seq.map (fun (l,p)->l,(p|>Seq.map(fun(x,_)->x)))
242     let fn (app:Map<local_id,int>,str:string) (p:premise) =
243         let (a:Map<local_id,int>,s:string) =
244             let l,r = premise p rule.typemap app rule_nr
245             if flags.debug then
246                 let stab_adds = p|>get_definitions|>List.map symbol_table_add |> String.concat ""
247                 l,(r+stab_adds)
248             else l,r
249         a,(str+s)
250     let lines =
251         linegroups |> Seq.mapi
252         (fun idx (linenumber,premisses)->
253             let breakpoint =
254                 if flags.debug then
255                     sprintf "if(_DEBUG_breakpoints_%d[%d]){_DEBUG.breakpoint(\"%s\",%d,
256                         _DEBUG_symbol_table);}\n" rule_nr idx rule.definition.File linenumber
257                 else ""
258             let _,s = ((Map.empty,""),premisses) ||> Seq.fold fn
259                 s+breakpoint)
260             sprintf "{\n%s%sreturn %s;\n}\n%s:\n"
261             (if flags.debug then "var _DEBUG_symbol_table = new System.Collections.Generic.
262                 Dictionary<string,object>();\n" else "")
263             (rule.input|>List.mapi (fun i x->sprintf "var %s=_arg%d;\n%s" (mangle_local_id x) i (
264                 if flags.debug then symbol_table_add x else "")) |> String.concat "")
265             (lines|>String.concat "")
266             (mangle_local_id rule.output)
267             (print_label rule_nr)
268
269 let nr_of_actual_lines (rule:rule):int =
270     rule.premis |> Seq.map snd |> Seq.distinct |> Seq.length
271
272 let print_rule_bodies (rules:rule list) =
273     let len = rules |> List.scan (fun s r->s+(nr_of_actual_lines r)-1) 0 |> List.rev |> List
274         .tail |> List.rev |> List.zip rules
275     len |> List.mapi (fun x (a,b)->print_rule x a) |> String.concat ""
276
277 let generate_breakpoint_def (funcname:string) (rules:rule seq) =
278     let linenumbers = rules |> Seq.map (fun x->x.premis) |> Seq.map ((Seq.map snd)>>Seq.
279         distinct)
280     let subarrays = linenumbers |> Seq.mapi (fun i x->
281         let s =

```

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```
277     if funcname="_main" then
278       x |> Seq.mapi (fun i _-> if i=0 then "true" else "false") |> String.concat ","
279     else
280       x |> Seq.map (fun _-> "false") |> String.concat ","
281     sprintf "%s._DEBUG_breakpoints_%d=%new bool[]{%s};\n" funcname i s)
282 subarrays |> String.concat ""
283
284 let generate_breakpoint_decl (rules:rule seq) = rules |> Seq.mapi (fun i _-> sprintf "
285     public static bool[] _DEBUG_breakpoints_%d;\n" i) |> String.concat ""
286
287 let print_main (input:fromTypecheckerWithLove) =
288   let rule = input.main
289   let return_type = mangle_type rule.typemap.[rule.output]
290   let body = sprintf "static %s body() {\n%sthrow new System.MissingMethodException();\n}"
291     return_type (print_rule_bodies [rule])
292   let debug_init =
293     if flags.debug then
294       let foo = input.funcs |> Map.toSeq |> Seq.map (fun(k,(rules,pos))->
295         generate_breakpoint_def (mangle_id k) rules) |> String.concat ""
296       foo+(generate_breakpoint_def "_main" [rule])+(print_debug_tree input.funcs input.
297         main)
298     else ""
299   let main = sprintf "static void Main() {\n%sthrow new System.Console.WriteLine(System.String.
300     Format(\"{0}\", body()));\n}" debug_init
301   sprintf "class _main{\n%sthrow new System.MissingMethodException();\n}" (if flags.debug then generate_breakpoint_decl [rule]
302     else "") body main
303
304 let rec print_tree (lookup:fromTypecheckerWithLove) (ns:List<NamespacedItem>) :string =
305   let build_func (name:string) (rules:rule list) =
306     let breakpoints = if flags.debug then generate_breakpoint_decl rules else ""
307     let rule = List.head rules
308     let args = rule.input |> Seq.mapi (fun nr id-> sprintf "public %s _arg%d;\n" (
309       mangle_type rule.typemap.[id]) nr) |> String.concat ""
310     let ret_type = mangle_type rule.typemap.[rule.output]
311     let rules = print_rule_bodies rules
312     sprintf "class %s {\n%sthrow new System.MissingMethodException();\n}"
313       ;\n}\n" (CSharpMangle name) args breakpoints ret_type rules
314   let print_base_types (ns:List<NamespacedItem>) =
315     let types = ns |> List.fold (fun types item -> match item with Data (_,v) -> v.
316       outputType::types | _ -> types) [] |> List.distinct
317     let print t = sprintf "public class %s {\n" (t|>remove_namespace_of_type|>mangle_type)
318     List.map print types
319   let go ns =
320     match ns with
321     | Ns(n,ns) -> sprintf "namespace %s {\n" (CSharpMangle n) (print_tree lookup
322       ns)
323     | Data(n,d) -> sprintf "public class %s: %s {\n" (CSharpMangle n) (d.outputType
324       |>remove_namespace_of_type|>mangle_type) (d.args|>List.mapi field|>String.concat "")
325     | Function(name,rules) -> build_func name rules
326     | Lambda(number,rule) -> build_func (sprintf "_lambda%d" number) [rule]
327   (print_base_types ns)@(ns|>List.map go)|>String.concat "\n"
328
329 let get_locals (ps:(premise*int) list) :local_id list =
330   ps |> List.collect (fun (p,_) ->
331     match p with
332     | Literal x -> [x.dest]
333     | Conditional x -> [x.left;x.right]
334     | Destructor x -> x.source::x.args
335     | LambdaClosure x -> [x.dest]
336     | FuncClosure x -> [x.dest]
337     | DotNetCall x -> [x.dest]
338     | DotNetStaticCall x -> [x.dest]
339     | DotNetConstructor x -> [x.dest]
340     | DotNetGet x -> [x.dest]
341     | DotNetSet x -> [x.src]
342     | ConstructorClosure x -> [x.dest]
343     | Application x -> [x.dest]
```

```

333 | ApplicationCall      x -> [x.closure;x.dest;x.argument] )
334
335 let validate (input:fromTypecheckerWithLove) :bool =
336 let print_local_id (id:local_id) = match id with Named(x)->x | Tmp(x)->sprintf "
    temporary(%d)" x
337 let print_id (id:Id) = String.concat "" (id.Name::id.Namespace)
338 let check_typemap (id:Id) (rule:rule) :bool =
339 let expected = (get_locals rule.premis) @ (rule.output::rule.input) |> List.distinct
    |> List.sort
340 let received = rule.typemap |> Map.toList |> List.map (fun (x,_)->x) |> List.sort
341 if expected = received then true
342 else
343 let missing = expected |> List.filter (fun x -> received |> List.exists (fun y->x=y)
    |> not)
344 let extra = received |> List.filter (fun x -> expected |> List.exists (fun y->x=y)
    |> not)
345 do ice()
346 do printf "\uincorrect\u typemap \u in \u rule \u %s: \u n \u missing \u %A \u n \u extra: \u %A \u n" (print_id id
    ) missing extra
347 false
348 let check_dest_constness (id:Id) (rule:rule) (success:bool):bool =
349 let per_premisse (statementnr:int) (set:Set<local_id>,success:bool) (premise:
    premise,i:int) :Set<local_id>*bool =
350 let check (set:Set<local_id>,success:bool) (local:local_id) =
351 if set.Contains(local) then
352 do ice()
353 do printf "\u %s \u assigned \u twice \u in \u rule \u %s, \u statement \u %d \u on \u line \u %d \u n" (
    print_local_id local) (print_id id) statementnr i
354 set,false
355 else set.Add(local),success
356 match premise with
357 | Literal x          -> check (set,success) x.dest
358 | Conditional _      -> set,success
359 | Destructor x       -> x.args |> Seq.fold check (set,success)
360 | ConstructorClosure x -> check (set,success) x.dest
361 | FuncClosure x      -> check (set,success) x.dest
362 | LambdaClosure x    -> check (set,success) x.dest
363 | DotNetCall x       -> check (set,success) x.dest
364 | DotNetStaticCall x -> check (set,success) x.dest
365 | DotNetConstructor x -> check (set,success) x.dest
366 | DotNetGet x        -> check (set,success) x.dest
367 | DotNetSet x        -> set,success
368 | Application x      -> check (set,success) x.dest
369 | ApplicationCall x  -> check (set,success) x.dest
370 let _,ret = rule.premis |> foldi per_premisse (Set.empty,success)
371 ret
372 (true,input.funcs) ||> Map.fold (fun (success:bool) (id:Id) (rules,position)->
373 if rules.IsEmpty then
374 do ice()
375 do printf "\u empty \u rule: \u %s \u n" (print_id id)
376 false
377 else
378 (true,input.main::rules) ||> List.fold (fun (success:bool) (rule:rule) -> if
    check_typemap id rule then (check_dest_constness id rule success) else false))
379
380 let failsafe_codegen(input:fromTypecheckerWithLove) :Option<string>=
381 do flags <- input.flags
382 if validate input then
383 let foo = input |> construct_tree |> print_tree input
384 let debug = if flags.debug then System.IO.File.ReadAllText("_DEBUG.cs.txt") else ""
385 debug+foo+(print_main input) |> Some
386
387 else None

```

C.5 Mangle.fs

```

1 module Mangle

```

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```
2 open Common
3 open CodegenInterface
4
5 let genericMangle (name:string) :string =
6   let readables =
7     Map.ofArray <| Array.zip " !$%&'*,+,-./\|:;<=>?@^_`|~"B [|
8       "bang";"hash";"cash";"perc";"amp";"prime";"star";"plus";"comma";
9       "dash"; "dot";"slash";"back";"colon";"semi";"less";"great";
10      "equal";"quest";"at";"caret";"under";"tick";"pipe";"tilde"|]
11   let mangleChar c =
12     if (c>='A'&&c<='Z') || (c>='a'&&c<='z') || (c>='0'&&c<='9') then
13       sprintf "%c" c
14     else
15       let lookup = readables |> Map.tryFind (System.Convert.ToByte c)
16       match lookup with
17       | None -> failwith <| sprintf "ERROR(codegen):_expecting_printable_ASCII_
character,_got_(0x%04X)" (System.Convert.ToUInt16(c))
18       | Some x -> sprintf "%s" x
19   name |> String.collect mangleChar
20
21 let CSharpMangle (name:string) :string =
22   let keywords = Set.ofArray [| "abstract" ; "as" ; "base" ; "bool" ;
23     "break" ; "byte" ; "case" ; "catch" ; "char" ; "checked" ; "class" ; "const" ;
24     "continue" ; "decimal" ; "default" ; "delegate" ; "do" ; "double" ; "else" ;
25     "enum" ; "event" ; "explicit" ; "extern" ; "false" ; "finally" ; "fixed" ;
26     "float" ; "for" ; "foreach" ; "goto" ; "if" ; "implicit" ; "in" ; "int" ;
27     "interface" ; "internal" ; "is" ; "lock" ; "long" ; "namespace" ; "new" ;
28     "null" ; "object" ; "operator" ; "out" ; "override" ; "params" ; "private" ;
29     "protected" ; "public" ; "readonly" ; "ref" ; "return" ; "sbyte" ; "sealed" ;
30     "short" ; "sizeof" ; "stackalloc" ; "static" ; "string" ; "struct" ;
31     "switch" ; "this" ; "throw" ; "true" ; "try" ; "typeof" ; "uint" ; "ulong" ;
32     "unchecked" ; "unsafe" ; "ushort" ; "using" ; "virtual" ; "void" ;
33     "volatile" ; "while" |]
34   let name = genericMangle name
35   if keywords.Contains(name) then sprintf "@%s" name else name
36
37 let rec mangle_type_suffix(t:Type):string=
38   match t with
39   | DotNetType (id) -> id.Namespace@[id.Name] |> Seq.map genericMangle |> String.concat "
_ns"
40   | McType (id) -> id.Namespace@[id.Name] |> Seq.map genericMangle |> String.concat "
_ns"
41   | TypeApplication (fn,lst) -> (mangle_type_suffix fn)+"_of"+(lst |> List.map
mangle_type_suffix |> String.concat "_t")
42
43 let rec remove_namespace_of_type(t:Type):Type=
44   match t with
45   | DotNetType (id) -> DotNetType({id with Namespace=[]})
46   | McType (id) -> McType({id with Namespace=[]})
47   | TypeApplication (fn,lst) -> TypeApplication((remove_namespace_of_type fn),lst)
48
49 let rec mangle_type(t:Type):string=
50   match t with
51   | DotNetType (id) -> id.Namespace@[id.Name] |> Seq.map CSharpMangle |> String.concat "."
52   | McType (id) -> id.Namespace@[id.Name] |> Seq.map (fun x->if x="System" then "
_System" else CSharpMangle x) |> String.concat "."
53   | TypeApplication (fn,lst) -> (mangle_type fn)+"_of"+(lst|>List.map mangle_type_suffix|>
String.concat "_t")
54
55 let mangle_local_id n = match n with Named x -> CSharpMangle x | Tmp x -> sprintf "_tmp%d"
x
56 let mangle_id (id:Id) =
57   if id.Namespace =[] && id.Name="main" then "_main"
58   else (id.Name::id.Namespace) |> List.rev |> List.map (fun x->if x="System" then "_System
" else CSharpMangle x) |> String.concat "."
59 let mangle_lambda (id:LambdaId) = sprintf "%s._lambda%d" (id.Namespace|>List.rev|>String.
concat ".") id.Name
```

C.6 _debug.cs

```
1 struct _debug {
2     public static System.Windows.Forms.TreeView program_tree = new System.Windows.Forms.
        TreeView();
3     public static bool[][][] breakpoints;
4     public static void breakpoint(string filename, int line, System.Collections.Generic.
        Dictionary<string, object> stab) {
5         // table
6         var table = new System.Windows.Forms.ListView();
7         table.GridLines = true;
8         table.Dock = System.Windows.Forms.DockStyle.Fill;
9         table.View = System.Windows.Forms.View.Details;
10        table.Columns.Add("name", -2, System.Windows.Forms.HorizontalAlignment.Left);
11        table.Columns.Add("value", -2, System.Windows.Forms.HorizontalAlignment.Left);
12        foreach (var x in stab) {
13            table.Items.Add(new System.Windows.Forms.ListViewItem(new string[] { x.Key, System.
                String.Format("{0}", x.Value) }));
14        }
15
16        var tablepanel = new System.Windows.Forms.Panel();
17        tablepanel.Dock = System.Windows.Forms.DockStyle.Fill;
18        tablepanel.Controls.Add(table);
19
20        // tree
21        program_tree.CheckBoxes = true;
22        program_tree.Dock = System.Windows.Forms.DockStyle.Fill;
23        program_tree.ExpandAll();
24        for (int filenr = 0; filenr < breakpoints.Length; filenr++) {
25            for (int funcnr = 0; funcnr < breakpoints[filenr].Length; funcnr++) {
26                for (int ruln = 0; ruln < breakpoints[filenr][funcnr].Length; ruln++) {
27                    for (int premnr = 0; premnr < breakpoints[filenr][funcnr][ruln].Length; premnr
                ++) {
28                        program_tree.Nodes[filenr].Nodes[funcnr].Nodes[ruln].Nodes[premnr].Checked =
                            breakpoints[filenr][funcnr][ruln][premnr];
29                    }
30                }
31            }
32        }
33
34        var treepanel = new System.Windows.Forms.Panel();
35        treepanel.Dock = System.Windows.Forms.DockStyle.Fill;
36        treepanel.Controls.Add(program_tree);
37
38        // split
39        var split = new System.Windows.Forms.SplitContainer();
40        split.SplitterDistance = 100;
41        split.Dock = System.Windows.Forms.DockStyle.Fill;
42        split.Panel1.Controls.Add(treepanel);
43        split.Panel2.Controls.Add(tablepanel);
44
45        var splitform = new System.Windows.Forms.Form();
46        splitform.Controls.Add(split);
47        splitform.MinimumSize = new System.Drawing.Size(100, 100);
48        splitform.Text = filename + ":" + line;
49
50        var buttons = new System.Windows.Forms.Button[4];
51        buttons[0] = new System.Windows.Forms.Button();
52        buttons[0].Text = "continue";
53        buttons[0].DialogResult = System.Windows.Forms.DialogResult.Ignore;
54        buttons[1] = new System.Windows.Forms.Button();
55        buttons[1].Text = "abort";
56        buttons[1].DialogResult = System.Windows.Forms.DialogResult.Abort;
57        /*buttons[2] = new System.Windows.Forms.Button();
58        buttons[2].Text = "step in";
59        buttons[2].DialogResult = System.Windows.Forms.DialogResult.OK;
60        buttons[3] = new System.Windows.Forms.Button();
```


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```
61     buttons[3].Text = "step over";
62     buttons[3].DialogResult = System.Windows.Forms.DialogResult.Yes;*/
63
64     var collection = new System.Windows.Forms.FlowLayoutPanel();
65     collection.Dock = System.Windows.Forms.DockStyle.Bottom;
66     collection.Controls.AddRange(buttons);
67     collection.AutoSize = true;
68     collection.AutoSizeMode = System.Windows.Forms.AutoSizeMode.GrowAndShrink;
69
70     splitform.Controls.Add(collection);
71
72     var result = splitform.ShowDialog();
73
74     for (int filenr = 0; filenr < breakpoints.Length; filenr++) {
75         for (int funcnr = 0; funcnr < breakpoints[filenr].Length; funcnr++) {
76             for (int rulenr = 0; rulenr < breakpoints[filenr][funcnr].Length; rulenr++) {
77                 for (int premnr = 0; premnr < breakpoints[filenr][funcnr][rulenr].Length; premnr
78 ++) {
79                     breakpoints[filenr][funcnr][rulenr][premnr] = program_tree.Nodes[filenr].Nodes
80 [funcnr].Nodes[rulenr].Nodes[premnr].Checked;
81                 }
82             }
83         }
84
85         switch (result) {
86             /*case System.Windows.Forms.DialogResult.OK: // step in
87                 return;
88             case System.Windows.Forms.DialogResult.Yes: // step over
89                 return; */
90             case System.Windows.Forms.DialogResult.Ignore: // continue
91                 return;
92             case System.Windows.Forms.DialogResult.Abort:
93                 System.Environment.Exit(0);
94                 return;
95         }
96     }
```

C.7 Listtest.fs

```
1  module CodegenTest
2
3  open Common
4  open CodegenInterface
5
6  let test_data:fromTypecheckerWithLove=
7      let int_t:Type = DotNetType({Namespace=["System"];Name="Int32"})
8      let float_t:Type = DotNetType({Namespace=["System"];Name="Single"})
9      let star_t:Type = TypeApplication((McType({Namespace=["test";"mc"];Name="star"})),[
10         int_t;float_t])
11      let pipe_t:Type = TypeApplication((McType({Namespace=["test";"mc"];Name="pipe"})),[
12         int_t;float_t])
13      let comma_id:Id = {Namespace=["test";"mc"];Name="comma"}
14      let left_id:Id = {Namespace=["test";"mc"];Name="left"}
15      let right_id:Id = {Namespace=["test";"mc"];Name="right"}
16      let comma_data:data =
17          {
18              args=[int_t; float_t; ];
19              outputType=star_t;
20          }
21      let left_data:data =
22          {
23              args=[int_t;];
24              outputType=pipe_t;
25          }
26      let right_data:data =
```

```

25     {
26       args=[float_t;];
27       outputType=pipe_t;
28     }
29   let datas = [comma_id,comma_data; left_id,left_data; right_id,right_data]
30   let main = {input=[];output=Tmp(0);premis=[];typemap=Map.empty;side_effect=true}
31   {funcs=Map.empty;lambdas=Map.empty;datas=datas;main=main;assemblies=[]}
32
33 let list_test:fromTypecheckerWithLove =
34   let int_t:Type = DotNetType({Namespace=["System"];Name="Int32"})
35   let add_t:Type = Arrow(int_t,Arrow(int_t,int_t))
36   let add_id:Id = {Namespace=["builtin"];Name="add"}
37
38   // data "nil" -> List
39   let list_t:Type = TypeApplication((McType({Namespace=["mc";"test"];Name="List"})),[
40     int_t])
41   let nil_id:Id = {Namespace=["test";"mc"];Name="nil"}
42   let nil_data:data =
43     {
44       args=[];
45       outputType=list_t;
46     }
47
48   // data Int -> ":" -> List -> List
49   let append_id:Id = {Namespace=["test";"mc"];Name=":"}
50   let append_data:data =
51     {
52       args=[int_t; list_t];
53       outputType=list_t;
54     }
55
56   // length nil -> 0
57   let length_t:Type= Arrow (list_t,int_t)
58   let length_id:Id = {Namespace=["test";"mc"];Name="length"}
59   let length_nil:rule =
60     {
61       side_effect=false
62       input=[Tmp(0)]
63       premis=[Destructor({source=Tmp(0); destructor=nil_id; args=[]})
64         Literal ({value=I32(0);dest=Tmp(1)}) ]
65       output=Tmp(1)
66       typemap=Map.ofSeq [Tmp(0),list_t
67         Tmp(1),int_t ]
68     }
69
70   // length xs -> r
71   // -----
72   // length x::xs -> add^builtin r 1
73   let length_append:rule =
74     {
75       side_effect=false
76       input=[Tmp(0)]
77       premis=[Destructor({source=Tmp(0); destructor=append_id; args=[Named("x");Named("xs"
78         )])])
79         FuncClosure({func=length_id; dest=Tmp(1)})
80         ApplicationCall({closure=Tmp(1); argument=Named("xs"); dest=Named("r");
81         side_effect=false})
82         Literal({value=I32(1); dest=Tmp(2)})
83         DotNetStaticCall({func={Name="+";Namespace=["System";"Int32"]};args=[Named("
84         r");Tmp(2)];dest=Tmp(3); side_effect=false})
85     ]
86     output=Tmp(3)
87     typemap=Map.ofSeq [Tmp(0),list_t
88       Named("x"),int_t
89       Named("xs"),list_t
90       Tmp(1),Arrow(list_t,int_t)
91       Named("r"),int_t

```

```

88             Tmp(2),int_t
89             Tmp(3),int_t ]
90     }
91
92     let datas = [nil_id,nil_data; append_id,append_data]
93     let Funcs = Map.ofSeq <| [length_id,[length_nil;length_append]]
94     let main =
95     {
96         input=[]
97         output=Tmp(7)
98         premis=[ConstructorClosure({func=nil_id;dest=Named("end")})
99                 Literal({value=I32(2);dest=Named("second")})
100                 ConstructorClosure({func=append_id;dest=Tmp(0)})
101                 Application({closure=Tmp(0); argument=Named("second"); dest=Tmp(1)})
102                 Application({closure=Tmp(1); argument=Named("end"); dest=Tmp(2)})
103                 Literal({value=I32(1);dest=Named("first")})
104                 Conditional({left=Named("first");predicate=Less;right=Named("second")})
105                 ConstructorClosure({func=append_id;dest=Tmp(3)})
106                 Application({closure=Tmp(3); argument=Named("first"); dest=Tmp(4)})
107                 Application({closure=Tmp(4); argument=Tmp(2); dest=Tmp(5)})
108                 FuncClosure({func=length_id; dest=Tmp(6)})
109                 ApplicationCall({closure=Tmp(6); argument=Tmp(5); dest=Tmp(7); side_effect=
110                 false})]
111         typemap=Map.ofSeq [Named("end"),list_t
112                           Named("second"),int_t
113                           Named("first"),int_t
114                           Tmp(0),Arrow(int_t,(Arrow(list_t,list_t)))
115                           Tmp(1),Arrow(list_t,list_t)
116                           Tmp(2),list_t
117                           Tmp(3),Arrow(int_t,(Arrow(list_t,list_t)))
118                           Tmp(4),Arrow(list_t,list_t)
119                           Tmp(5),list_t
120                           Tmp(6),Arrow(list_t,int_t)
121                           Tmp(7),int_t]
122     }
123     {funcs=Funcs;datas=datas;lambdas=Map.empty;main=main;assemblies=[]}

```

C.8 Balltest.fs

```

1  module balltest
2  open Common
3  open CodegenInterface
4
5  #nowarn "0058" // silences indentation warnings
6
7  let ball_func =
8      let vec2_t:Type = DotNetType({Namespace=["Microsoft";"Xna";"Framework"];Name="Vector2"})
9      let int_t:Type = DotNetType({Namespace=["System"];Name="Int32"})
10     let float_t:Type = DotNetType({Namespace=["System"];Name="Single"})
11     let ball_t:Type = McType({Namespace=["BouncingBall"];Name="Ball"})
12     let ball_id:Id = {Namespace=["BouncingBall"];Name="ball"}
13
14     let ball_data:data =
15     {
16         args=[vec2_t;vec2_t];
17         outputType=ball_t;
18     }
19
20     let void_t:Type = DotNetType({Name="void";Namespace=[]})
21
22     // update
23     let update_id:Id = {Namespace=["BouncingBall"];Name="update"}
24     let update_t:Type = float_t --> (ball_t --> ball_t)
25     let update_fall_down:rule = {
26         side_effect = false
27         definition = { File="notreal.mc"; Line=9001; Col=1}

```

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```
28 input = [Named("dt");Named("b")]
29 output = Named("out")
30 premis =
31 [
32     // b -> ball(position velocity)
33     Destructor({source=Named("b");destructor=ball_id;args=[Named("position");Named("
velocity")]}),1
34
35     // gety() -> y
36     DotNetGet({field="y"
37         instance = Named("position")
38         dest=Named("y") }),2
39
40     // y >= 0
41     Literal({value=F32(0.0f);dest=Named("zero")}),3
42     Literal({value=F32(500.0f);dest=Named("ground")}),3
43     Conditional({left=Named("y");predicate=LessEqual;right=Named("ground")}),3
44
45     // Vector2(0,9.81)
46     Literal({value=F32(98.1f);dest=Named("g")}),4
47     DotNetConstructor({func={Namespace=["Microsoft";"Xna";"Framework"];Name="Vector2"}
48         args=[Named("zero");Named("g")]
49         dest=Named("v2")
50         side_effect=false}),4
51
52     // dotproduct
53     DotNetStaticCall({func={Namespace=["Microsoft";"Xna";"Framework";"Vector2"];Name="
op_Multiply"}
54         args=[Named("v2");Named("dt")]
55         dest=Named("outerProduct")
56         side_effect=false}),5
57
58     // sum
59     DotNetStaticCall({func={Namespace=["Microsoft";"Xna";"Framework";"Vector2"];Name="
op_Addition"}
60         args=[Named("velocity");Named("outerProduct")]
61         dest=Named("updatedVelocity")
62         side_effect=false}),6
63
64     // dotproduct
65     DotNetStaticCall({func={Namespace=["Microsoft";"Xna";"Framework"];Name="
op_Multiply"}
66         args=[Named("updatedVelocity");Named("dt")]
67         dest=Named("outerProduct2")
68         side_effect=false}),7
69
70     // sum
71     DotNetStaticCall({func={Namespace=["Microsoft";"Xna";"Framework"];Name="
op_Addition"}
72         args=[Named("position");Named("outerProduct2")]
73         dest=Named("updatedPosition")
74         side_effect=false}),8
75
76     // Ball (updated_position, updated_velocity)
77     ConstructorClosure({func=ball_id;dest=next_tmp()}),9
78     Application({closure=current_tmp(); argument=Named("updatedPosition"); dest=
next_tmp()}),9
79     Application({closure=current_tmp(); argument=Named("updatedVelocity"); dest=Named(
"out")}),9
80 ]
81 typemap=
82 [
83     Named("dt"),float_t
84     Named("b"),ball_t
85     Named("out"),ball_t
86     Named("y"),float_t
87     Named("zero"),float_t
```

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```
88     Named("ground"),float_t
89     Named("velocity"),vec2_t
90     Named("position"),vec2_t
91     Named("g"),float_t
92     Named("v2"),vec2_t
93     Named("updatedPosition"),vec2_t
94     Named("updatedVelocity"),vec2_t
95     Named("outerProduct"),vec2_t
96     Named("outerProduct2"),vec2_t
97     reset_tmp(),(vec2_t --> (vec2_t --> ball_t))
98     next_tmp(),(vec2_t --> ball_t)
99   ] |> Map.ofSeq
100 }
101
102 do reset()
103 let update_bounce:rule = {
104   side_effect = false
105   definition = { File="notreal.mc"; Line=9001; Col=2}
106   input = [Named("dt");Named("b")]
107   output = Named("out")
108   premis =
109     [
110       // b -> ball(position velocity)
111       Destructor({source=Named("b");destructor=ball_id;args=[Named("position");Named("velocity")]}),10
112
113       // gety() -> y
114       DotNetGet({field="Y"
115         instance = Named("position")
116         dest=Named("y") }),11
117
118       // getx() -> x
119       DotNetGet({field="X"
120         instance = Named("position")
121         dest=Named("x") }),12
122
123       // y >= 0
124       Literal({value=F32(500.0f);dest=Named("ground")}),13
125       Conditional({left=Named("y");predicate=Greater;right=Named("ground")}),13
126
127       // Vector2(pos.x,zero)
128       DotNetConstructor({func={Namespace=["Microsoft";"Xna";"Framework"];Name="Vector2"}
129         args=[Named("x");Named("ground")]
130         dest=Named("updatedPosition")
131         side_effect=false}),14
132
133       DotNetStaticCall({func={Namespace=["Microsoft";"Xna";"Framework";"Vector2"];Name="op_Subtraction"}
134         args=[Named("velocity")]
135         dest=Named("updatedVelocity")
136         side_effect=false}),15
137
138       // Ball (updated_position, updated_velocity)
139       ConstructorClosure({func=ball_id;dest=next_tmp()}),16
140       Application({closure=current_tmp(); argument=Named("updatedPosition"); dest=
141         next_tmp()}),16
142       Application({closure=current_tmp(); argument=Named("updatedVelocity"); dest=Named("out")}),16
143     ]
144   typemap=
145     [
146       Named("dt"),float_t
147       Named("b"),ball_t
148       Named("out"),ball_t
149       Named("y"),float_t
150       Named("x"),float_t
```

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```
151         Named("ground"),float_t
152         Named("velocity"),vec2_t
153         Named("position"),vec2_t
154         Named("updatedPosition"),vec2_t
155         Named("updatedVelocity"),vec2_t
156         reset_tmp(),(vec2_t --> (vec2_t --> ball_t))
157         next_tmp(),(vec2_t --> ball_t)
158     ] |> Map.ofSeq
159 }
160 let Funcs = Map.ofSeq <| [update_id,([update_fall_down;update_bounce],{File="decl.mc";
    Line=1337;Col=2})]
161 let main = {
162     definition = { File="notreal.mc"; Line=9001; Col=2}
163     input=[]
164     output=Named("ret")
165     premis=[
166         Literal({dest=Named("x1");value=F32(20.0f)}),100
167         Literal({dest=Named("y1");value=F32(10.0f)}),101
168         DotNetConstructor({dest=Named("a");func={Namespace=["Microsoft";"Xna";"Framework"
    ];Name="Vector2";args=[Named("x1");Named("y1");side_effect=false]}),102
169         Literal({dest=Named("x2");value=F32(10.0f)}),103
170         Literal({dest=Named("y2");value=F32(30.0f)}),104
171         DotNetConstructor({dest=Named("b");func={Namespace=["Microsoft";"Xna";"Framework"
    ];Name="Vector2";args=[Named("x2");Named("y2");side_effect=false]}),105
172         DotNetStaticCall({dest=Named("c");func={Namespace=["Microsoft";"Xna";"Framework";"
    Vector2"];Name="op_Addition";args=[Named("a");Named("b");side_effect=false]}),106
173         DotNetCall({dest=Named("nil");instance=Named("c");func="Normalize";args=[];
    side_effect=false;mutates_instance=true;}),107
174         DotNetSet({src=Named("y2");instance=Named("c");field="X"}),108
175         DotNetGet({dest=Named("ret");instance=Named("c");field="X"}),109
176     ]
177     typemap=Map.ofList <| [
178         Named("x1"),float_t
179         Named("y1"),float_t
180         Named("x2"),float_t
181         Named("y2"),float_t
182         Named("a"),vec2_t
183         Named("b"),vec2_t
184         Named("c"),vec2_t
185         Named("nil"),void_t
186         Named("ret"),float_t
187     ]
188     side_effect=true
189 }
190 {funcs=Funcs;datas=[ball_id,ball_data];lambdas=Map.empty;main=main;assemblies=["
    Microsoft.Xna.Framework.dll"];flags={debug=true}}
```