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Compilation of a dynamic language Generators into MSIL

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Title: Compilation of a dynamic language Generators into MSIL

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Abstract: The goal of this thesis is to design and implement support for generators within the Peachpie framework, a PHP to CIL compiler. Generators are the simplest form of methods that resume from the same state in which they returned earlier when called repeatedly. The reference PHP interpreter Zend engine supports generators natively. Due to that fact generators in PHP are support a number of features not usually seen in other languages. CIL on the other hand does not have a native support for generators. Therefore, languages build on top of CIL (e.g. C#, F#) have to implement them by other means such as by rewriting the original generator methods into state machines. In this thesis we will design and implement support for generators through semantic tree transformations. All that with the intention of keeping the maximum possible compatibility with reference PHP generators. We will also make a comparison to generators in C# whose main implementation also uses CIL as a backend.

Keywords: compiler php msil .net generators roslyn peachpie

Contents

Introduction

Despite a slow decline in recent years [TIOBE, 2017], PHP is still one of the main languages used for a server side programming on the web [Stack Overflow, 2017]. Its only two relevant implementations are the reference and almost exclusively used Zend engine[1] and slowly emerging HHVM by Facebook[2]. Both of them are standalone virtual machines and neither of them supports easy interfacing with the outside world. Hence, it is quite difficult to share code between a web backend and, for example, a mobile or traditional desktop application.

Fortunately, there is a solution in the form of a Peachpie project[3] that is being researched at the Charles University. The project aims to provide a compiler from PHP to ".NET bytecode" CIL[4] and a reimplementation of PHP base class library, thus creating a bridge between PHP and the whole .NET ecosystem. Due to it being a full compiler that takes PHP sources and spits out .NET assemblies indistinguishable from those created by other .NET languages compilers (e.g C#, F# or IronPython) it provides both ways interoperability. It enables both calling normal unmodified .NET libraries from PHP and vice versa. Also, thanks to an extensive compile-time type analysis and proven .NET just in time compiler (RiuJIT) it achieves better performance than reference Zend engine in certain operations [Míšek, 2017, Fistein and Míšek, 2016 - 2017].

PHP, like many other modern languages, has a first class support for generators. Simply put, generators are methods that resume computation from the very place and with the same state they returned at previously when called repeatedly. They are usually used for generating large sequences of data lazily, hence the name generators. Since the execution state gets saved automatically on the special pause and return places (usually called yields) one can write an algorithm as if the sequence was being created at once and only insert yields at appropriate times, e.g. when a new item gets created. The language handles the rest. Each subsequent call to the generator method resumes computation from the last evaluated yield and continues to the next one, e.g. creating a new element each time.

The Zend engine has a native support for generators. It intrinsically understands yields and is, on their evaluation, able to save the state of current execution [Popov, 2017]. CIL has no such first class support. For that reason languages built on top of CIL have to implement generators through other means [Lippert, 2008]. Usually by rewriting generator methods into state machines with explicit state saving before each yield and state retrieval in the beginning.

That is exactly what this thesis covers. It describes the design and implementation of support for PHP generators within the Peachpie compiler through semantic tree transformations, implementation of new semantic tree nodes, and extensions to Peachpie runtime library. In the implementation parts it tries to not only plainly cover the code but also to depict the decision process that led to choosing certain approaches over others. During the whole work we will compare

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[1]zend.com/en/community/php

[2]hhvm.com/

[3]peachpie.io/

[4]Chapter 2.1

our approach with the one taken by C# team and its compiler Roslyn. C# was chosen as a reference language due to it being the prominent language in .NET platform.

While the goal is to implement support for generators with as much original PHP semantic as possible, due to the scope of this work we will not discuss the specific implementation of all PHP generators features. Namely, we will not cover handling yields in exception control blocks (try, catch, finally) in detail and will leave its implementation for future work.

Thesis structure

This thesis is divided into seven chapters. The first one covers general concepts of generators both in PHP and in other languages, explaining what they are, what features and limitations do they have, and where they stand in regards to iterators.

The second chapter briefly introduces the .NET platform and its intermediate language CIL. The third is all about the Peachpie project. It describes its architecture focusing mainly on the semantic tree data structure and CIL emit phase of the compiler. In fourth chapter we take a look at how generators are implemented in C#'s Roslyn and PHP's Zend engine. Especially the Roslyn's approach is important because it serves as a basis for our own implementation.

Generators within Peachpie is the focus of the fifth chapter which itself is further divided into five more sections. First describes an implementation of generators limited to circa C# generators. It builds on the theoretical basis described in previous section about Roslyn's approach. Second proposes theoretical algorithm to handle yield as expression. Third talks about implementation of said algorithm within peachpie. Fourth briefly mentions possible solutions for yields in exception handling blocks. And the fifth is about possible future work that could be done for generators support within peachpie.

The sixth chapter concludes and summarizes the whole thesis. And last but not least the final chapter provides a lightweight user documentation for the peachpie project and overview of attachments.

1. Generators

1.1 Iterators

Before going into generators we need to define iterators first. Iterators, as their name suggests, represent a state of iteration of some sequence backed by either themselves or some other object. In both C# and PHP they can be arbitrary objects implementing an *Iterator*[1] (for PHP) or an *IEnumerator*[2] (in C#) interface.

Both of these contain a number of methods (Figure 1.1). However, for now we will focus on only two of them they both share, *current* and *next*. The first one - *current* - should always return the element the iterator is currently pointing at. As such it should never modify the state of the iterator and should generally be side effect free. The second one, *next*, should advance the iterator to the next item effectively changing what element the *current* method returns.

Iterator
+ current(): PhpValue
+ key(): PhpValue
+ next(): void
+ rewind(): void
+ valid(): boolean

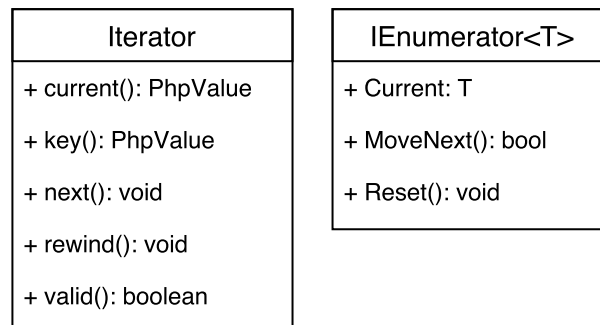| IEnumerator<T> |
| --- |
| + Current: T |
| + MoveNext(): bool |
| + Reset(): void |

Figure 1.1: Iterator and IEnumerable interfaces.

Iterators serve, among other things, as a useful tool to handle large sequences of items. Instead of generating everything at once and then keeping it, for example, in an array one can simply create an iterator that generates and serves the elements one by one. This enables lower memory footprint because there is no not need to ever keep all the elements in memory at once.

Furthermore instead of spending a lot of resources at once in the beginning to create the whole sequence the iterator can now spend just a little bit for each element's creation when the *next* method is called. Though the final price is the same regardless it enables a more even distribution of the performance hit. Also, one does not need to pay for the elements that do not get created - the ones that are not iterated over.

There is one problem with iterators, though. They are quite tedious to write. The main issue stems from the fact that unlike in a normal method in which you would create the whole sequence at once in the iterator's *next* method you need to always explicitly save and then retrieve the current state of the execution. There is a lot of boilerplate associated with them as well. You need to create a new type and implement a number of methods that do not actually do anything useful.

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[1][PHP.Net]
[2][MSDN]

To give an example (Listing 1), creating an array of numbers 1 to n is a straightforward for loop with an assignment. In the case of an iterator's *next* method you need to first retrieve last used number, increase it by one, and then store it. You also need to implement a *current* method that returns the last stored index and a few other ones that are basically just a busywork.

```php
<?php
function by_one_at_once(){
  $result = [];
  for($i = 0; $i < 10; $i++){
    $result[] = $i;
  }
  return $result;
}

class byOneIterator implements Iterator {
  private $position = 0;

  public function rewind() {$this->position = 0;}
  public function key() {return $this->position;}
  public function current() {return $this->position; }
  public function next() {
  $curr_pos = $this->position;
    $curr_pos += 1;
    $this->position = $curr_pos;
  }
  public function valid(){ return ($this->position < 10); }
}
```

Listing 1: Method that creates everything at once and as an Iterator.

While for a monotone sequence of numbers even the iterator is still simple and readable it quickly stops to be the case with higher complexity of the iteration. The amount of code needed for state keeping increases quite quickly and an algorithm which would otherwise be really straightforward when used for the creation of the whole sequence at once gets convoluted. And that is where generators come into play.

1.2 Generators universally

Generators provide an easy way to write methods that return iterators while the code can be almost the same as if they returned whole sequences at once instead. All the transforming of the algorithm into the *next* method with its retrieving of the last state in the beginning and state saving after a new element gets set as *current* is handled transparently for the programmer. There is also no need to create a new type and implement other iterator's busywork methods with them. They automatically return correct and fully implemented iterators.

To achieve this a new keyword *yield* or *yield return* is usually introduced. It serves two purposes. First, it marks the spots where the *next* method of the returned iterator should stop executing and save the current state. Second, much like the *return* keyword it specifies a value being returned, in this case actually a value that should be set as *current* on the iterator.

To continue with our example of creating a sequence of numbers from 1 to n (Listing 2). One would write a generator method the same way a normal method generating the whole array with the only difference that instead of an assignment into a result array the for loop would contain a *yield* of the current index.

```php
<?php
function by_one_generator(){
  for($i = 0; $i < 10; $i++){
    yield $i;
  }
}
```

Listing 2: By one sequence as a generator.

An iterator returned from such generator method (Figure 1.2) would have a *next* method that would always start from the last encountered *yield*, execute update and condition part of the for loop, and then set a new element as the *current* one.
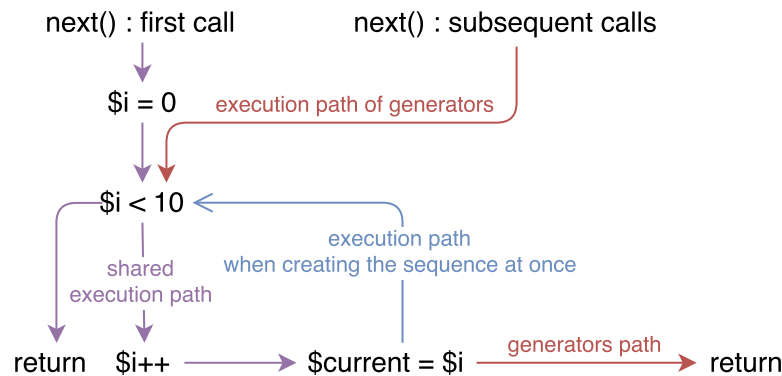
Figure 1.2: Generator's control flow graph.

1.3 Generators in PHP

Generators in PHP are not just about creating data, however. They support consuming data as well (Listing 3). Namely, one can send an arbitrary value into the returned iterator through its method called *send*. This method takes one argument - the value being sent, sets it as a result of the last *yield* expression, and resumes the evaluation the same way as *next* method would.

```php
<?php
function logger_generator(){
  $logger = new Logger();
  while(($line = yield) != "END"){
    $logger->log($line);
  }
  $logger->close();
}
class Logger{
  public function close(){ echo "END;";}
  public function log($line){ echo $line; }
}


$gen = logger_generator();
$gen->send("First!");
$gen->send("Second!");
$gen->send("END");
```

Listing 3: Generator method used as a logger.

This means that unlike in C# where *yield* is a statement and therefore can not be a part of a bigger computation or a function call in PHP *yield* can be literally anywhere, even in the place of a function call argument. This further complicates the state saving. In addition to all the local variables when *yield* is part of some bigger expression we need to save its state as well. And it needs to be done the right way to ensure correct order of execution.

Due to various design reasons [Lippert, 2009b] C# also limits where *yields* can happen in regards to exception control blocks. They are not allowed in *catch*[3] and *finally* blocks[4] altogether and can be only in *try* blocks[5] that do not have any associated catch blocks. PHP, on the other hand, allows yielding everywhere, be it in *try*, *catch*, or *finally* blocks.

1.4 Generators in other languages

These limitations are not unique to C#, however. Both F# and Visual Basic, the only other truly mainstream CIL based languages, also support generators with these restrictions. For them *yield* is just a statement that can not appear in certain exception handling blocks.

In fact, *yield* being an expression holding a send value is not even a feature all dynamic languages share. JavaScript, for example, had just a brief support[6] for such behavior and as of ECMA 2015 has *yield* only as a statement.

That, nonetheless, does not mean that PHP is completely unique in regards to generators. In python[7], another mainly interpreted dynamic language, *yields*

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[3][Lippert, 2009a]
[4][Lippert, 2009b]
[5][Lippert, 2009c]
[6][MDN]
[7][docs.python.org]

are expressions and are allowed in exception handling blocks almost the same way as in PHP. In Lua[8] they are implemented as a special version of coroutines and thus have an even wider set of features.

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[8][Lua.org]

2. .NET platform

The .NET platform, or any platform implementing the open CLI standard[1], stands on four pillars (Figure 2.1). The low level intermediate language CIL, the higher level languages such as C# and F# and their compilers to CIL, the base class library known as .NET framework, and - last but not least - the common language runtime, CLR, that actually executes the intermediate code.
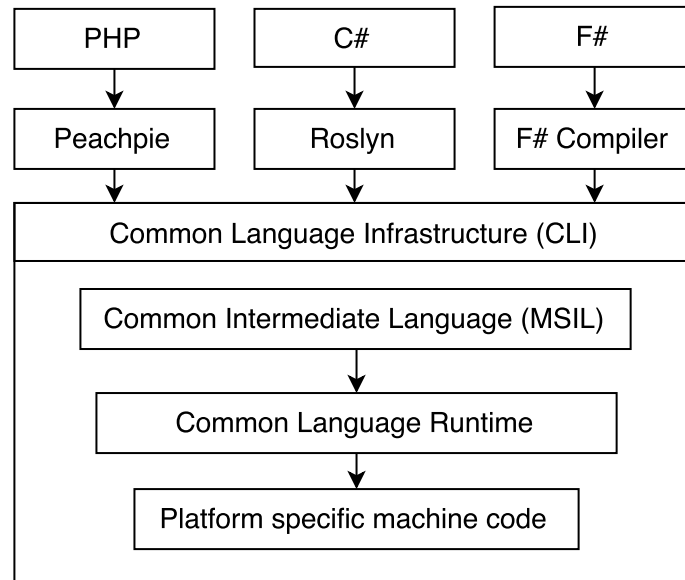

Figure 2.1: Common language infrastructure.

We will talk about the C# and Visual Basic compiler Roslyn later and neither the base class library nor the CLR is particularly interesting to us. The common intermediate language is, however.

2.1 Common intermediate language

CIL is an assembler defined by the common language infrastructure [ECMA-335, 2012] to be a shared basis for all CLI languages (C#, F#, IronPython, . . .) and runtime implementations (.NET, Mono, dotGNU, . . .). It is platform independent and as such does not natively run on any CPU architecture. Instead it must be either translated to the target platform's native code beforehand or - more commonly - executed by a virtual machine such as CLR.

Despite being an assembler, thus inherently low-level, CIL is actually object oriented and so has a deep understanding of reference types. Its instruction set reflects that with means to create new instances, access their members, and so on. The CLI specification also dictates that by default the CIL should be memory safe.

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[1][ECMA-335, 2012]

2.1.1 Evaluation stack

CIL is a stack based assembler, therefore without the notion for registers. Instead it defines a virtual evaluation stack. There are basically two types of instructions in CIL. Memory handling ones that either pop a value from the stack and store it in memory or load a value from memory and push it to the top and the ones that actually do some processing. These pop a few values from the stack, process them somehow, and then store the result on the top of the stack.

There are a few important things to note about the evaluation stack [ECMA-335, 2012, Sec. I.12.4]. Firstly, all parameters and local variables actually live there. They are not ordinary stack values, though. Their place gets reserved and later cleaned automatically and are not accessible through the normal push/pop instructions. Instead there are dedicated ones to work with them.

Secondly, when exiting a function the stack can not contain anything but the returned value. Thirdly, there are instructions only to work with its top. There is no way to query all the elements in the stack, get its height, or to completely save or load it to/from memory.

Lastly, while not a rule the stack is generally used as a store for temporal values instead of proper local variables. For example an expression $2 + 3 * 5$ (Listing 4) would usually result in the load of constants 2, 3, and 5, a multiplication operation $(3 * 5)$, at which point the stack would contain 2 and 15, and finally a plus operation that would leave the stack with 17 at its top.

All of these mean that you can not simply pause and save the execution of a method at arbitrary point with just one or even a few CIL instructions. To completely capture the current state you need not only to save all the local variables and parameters somewhere off the stack and but also do the same for every temporal value that might currently live on the stack. And there is no simple way to query what is currently. You need either to construct the information some other way or restrain yourself to saving the state only when the stack is empty.

2.1.2 Exception handling

The last notable thing about CIL is that it has a notion of exceptions and their handling blocks. Try, catch, and finally are all first class citizens in the language and are bound by a number of rules [ECMA-335, 2012, Sec. I.12.4].

CIL does not permit jumping / branching into any exception handling block[2] unless the source of the jump / branch is within the same block. You can only enter catch and finally regions through the proper exception handling mechanism. And lastly, to leave any of them[3] you need to do it via a designed instruction that, in case of try and catch blocks, ensures any potential finally region gets run. Therefore you can neither jump in the middle of a try block nor execute a catch / finally block without throwing a proper exception first.

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[2][ECMA-335, 2012, Sec. I.12.4.2.8.2.7]
[3][ECMA-335, 2012, Sec. I.12.4.2.8.2.8]

```csharp
public void M(int a) {
  int b = 3;
  int c = 5;
  G(a + b * c);
}
public int G(int a){/*Something*/}
```

```
.method public hidebysig instance void M (int32 a)
cil managed {
  .maxstack 4
  .locals init (
  [0] int32,
  [1] int32)
  IL_0000: nop        // Do nothing (No operation)
  IL_0001: ldc.i4.3  // Push 3 onto the stack as int32
  IL_0002: stloc.0   // Pop value from stack to local variable 0
  IL_0003: ldc.i4.5  // Push 5 onto the stack as int32
  IL_0004: stloc.1   // Pop value from stack to local variable 1
  IL_0005: ldarg.0   // Load argument 0 (this) onto the stack
  IL_0006: ldarg.1   // Load argument 1 onto the stack
  IL_0007: ldloc.0   // Load local variable 0 onto stack
  IL_0008: ldloc.1   // Load local variable 1 onto stack
  IL_0009: mul        // Multiply values
  IL_000a: add        // Add two values, returning a new value
  IL_000b: call instance int32 C::G(int32) // Call method
  ↪    indicated on the stack with arguments
  IL_0010: pop        // Pop value (returned by G) from the stack
  IL_0011: ret        // Return from method, possibly with a value
} // end of method C::M
```

Listing 4: Simple method in C# and CIL.

3. Peachpie project

3.1 Peachpie architecture

3.2 Peachpie compiler

3.3 Semantic graph

3.3.1 Statements and expressions

3.3.2 Graph structure

3.3.3 Graph creation

3.4 CIL emit phase

3.4.1 Code generator

3.4.2 Emit

3.4.3 Generate methods' invariants

3.5 Peachpie runtime library

4. Generators implementation in other platforms

4.1 CSharp and Roslyn

4.1.1 Iterator object and generator methods

4.1.2 Rewriter

4.1.3 Local variables parameters

4.1.4 Execution position

4.2 PHP and Zend Engine

5. Generators in Peachpie

5.1 Basic generators implementation

5.1.1 Iterator object

5.1.2 Next method implementation and local variables

5.1.3 Accessibility of fields on the Generator type

5.1.4 Context handling

5.1.5 Rewriter

5.1.6 Bound yield expression

5.1.7 Start block

5.1.8 Method symbol

5.2 Yield as an expression - theory

5.2.1 Possible approaches

5.2.2 Branch capture & yield splitting

5.2.3 Semantic tree transformation

5.2.4 Short circuit evaluation

5.3 Yield as an expression - implementation

5.3.1 Binding multiple elements

5.3.2 Capturing branches with yields

5.3.3 Correctness of modified capturing algorithm

5.3.4 Creating and keeping the pre-bound graph

5.3.5 Path between the root and yields

5.3.6 Conditioned branches

5.3.7 Implementation remarks

5.4 Yield in exception handling blocks

5.4.1 Yields and exception handling blocks in PHP

5.4.2 Solution in Peachpie

5.5 Future work

16

Conclusion

In previous four sections we have first described the fundamental concepts required for this thesis to even make sense, then designed an algorithm to support our feature, provided an overview of said algorithm's implementation, and, in the end, proposed possible expansions.

While the work on generators support within the Peachpie compiler is by no means done the shipped implementation provides a good foundation that can stand on its own. It brings support for all generator's features except for yields in exception handling blocks. And while that is an useful feature it is a more of an extension of generators than its fundamental building block. Other than that our implementation mimics the reference semantics faithfully while expanding upon the featureset usual in other CLI based languages such as in C#.

The goal of using as much existing architecture as possible and not creating unnecessary abstractions just for generators was also achieved. While there is still room for improvement all generators specific code is either cleanly separated or repurposed for use by other compiler components.

Lastly, while not an explicitly stated goal the compilation of generators is efficient. It does not introduce any new semantic tree or syntax tree traversals and only slightly increases the memory required for the binding phase. Due to separating all specific logic to a special binder it has absolutely no impact on binding and thus compiling non-generator methods.

In conclusion this thesis and the attached implementation fulfill all goals set by both the thesis assignment and us in the introduction section. On top of that it brings a self-contained functionality to a popular open source project.

Attachments

Attached to this thesis is a snapshot of Peachpie project's git repository. It contains not only the implementation that was done as the practical part of this thesis but also the rest of the complete project. A more up to date version can be found on github[1].

To query only commits done by the author of this thesis please filter out author *Petr Houška* or email *houskape@gmail.com.*

Compilation

The project's only implicit dependency is .NET Core runtime and optionally its CLI SDK. If you want to compile the project yourself you can download both of them from the official site[2], for Linux, Windows, or MacOSX.

After obtaining the .NET Core SDK please navigate to the folder with the Peachpie repository in your favourite terminal and:

```
dotnet restore  //download all external packages required
dotnet build    //build the complete solution
```

Structure

There are three components relevant for this thesis within the repository. The compiler binaries, the compiler implementation, and the generators tests. Below are listed paths to them and in case of the compiler's implementation also to some files containing the majority of our work to support generators.

1. src/Compiler/peach

2. src/CodeAnalysis

    (a) ./Semantics/SemanticsBinder.cs

    (b) ./Semantics/Graph/BuilderVisitor.cs

    (c) src/Peachpie.Runtime/std/Generator.cs

3. tests/generators

Manual testing

To compile an arbitrary PHP file into a .NET assembly with Peachpie invoke the compiler with a path to the PHP file as its first argument. The compiler assembly resides at aforementioned path and is called peach.exe or peach.dll depending of whether it was compiled for full .NET framework or .NET Core.

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[1] github.com/peachpiecompiler/peachpie
[2] microsoft.com/net/download/core

```
$\src\Compiler\peach> dotnet run .\test.php
```

Please do note that an assembly compiled this way will require PHP runtime libraries to run. These libraries can be found, for example, in the bin output of the compiler (peach) project.

Alternatively it is possible to use a Peachpie console application sample[3]. It includes a .msbuildproj file that configures the .NET Core CLI to download and use both the Peachpie compiler toolchain and required runtime libraries automatically. More about that approach can be found on a peachpie blog[4].

Automatic testing

The Peachpie project includes a comprehensive set of automatic tests. These consist of PHP files that get compiled by the Peachpie compiler and run by a .NET runtime. If there is a PHP runtime present in the current path environment variable they get run by it as well. The results are then compared to ensure Peachpie compilation keeps the original PHP semantics and is, in terms of runtime behaviour, indistinguishable from the reference implementation.

There is a number tests created as part of this thesis that ensure the implementation of generators support works correctly. They are located in a subfolder tests/generators. While they are in no particular order it is generally true that the higher their number the more complex aspect of generators they test. Below is a command that invokes all peachpie tests, including generator ones.

```
$\src\Tests\Peachpie.ScriptTests> dotnet test
```

Please do note that two tests usually fail on some machines because of encoding issues.

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[3]github.com/iolevel/peachpie-samples/tree/master/console-application
[4] peachpie.io/2017/04/tutorial-vs2017.html

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List of Figures

List of Abbreviations

CLI Common language infrastructure, open standard for runtime environment implemented by .NET, Mono, and others.

CIL Common intermediate language, object oriented assembler defined by *CLI* (also known as *MSIL* or *IL*).

CLR Common language runtime, virtual machine implementing the execution engine specified by *CLI*.

DLR Dynamic language runtime, set of libraries providing compiler and runtime services for dynamic languages build on top of *CLR*.

AST Abstract syntax tree, structured representation of the source code.

CFG Control flow graph, a semantic graph representing a method.