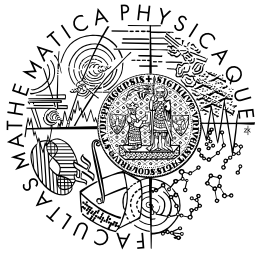

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MASTER THESIS

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System for extensions of the C# language

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Dedication.

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Contents

Introduction

Extensibility is an important feature of a programming language and its associated programming environment, because it allows adding new capabilities to the language. This way, a programmer can mold the language to their specific needs.

A common way to extend many languages is through libraries. Libraries let programmers use code written by someone else, which can be powerful, especially when combined with extensibility features built into programming languages, such as virtual functions or lambdas.

But libraries are restricted to the features offered by the used language, which can limit their usefulness.

This work describes a system for extending the C# language beyond what can be accomplished with libraries by user-provided extensions, which perform transformations of C# source code.

These extensions, themselves written in C#, should be easy to create, when compared with existing similar systems, and they should be efficient enough to be usable with code completion in a code editor or an integrated development environment (IDE), such as Microsoft Visual Studio.

To achieve this, the system is composed of two primary parts: the Syntax tree API (Application programming interface) and the Transformations API.

The Syntax tree API is used to represent the original C# source code, examine it, and modify it. The primary goal of this API is to be easy to use and abstract syntax trees fit that requirement well.

The Transformation API enhances the Syntax tree API by adding methods that split source code transformation into smaller parts. The inputs and outputs of each part are then tracked, which means that, after an initial full execution of the transformation, only the parts of the transformation whose inputs changed have to be re-executed. This is done to improve the performance of the system, especially when run from an IDE.

1. Background

The .NET ecosystem is composed of programming languages (including C#, F# and Visual Basic .NET), [1] .NET implementations (including .NET Framework, .NET Core and Mono), [2] class libraries, commonly distributed through the NuGet package manager, and tooling, including command-line tools and tools integrated into code editors and IDEs.

What unifies all these components is the Common Language Infrastructure (CLI), [3] which specifies binary file format for "assemblies". These contain compiled .NET code in the form of Intermediate Language (IL) and also metadata associated with this code.

The C# language [4] is an object-oriented programming language which is part of the .NET ecosystem. The C# compiler, code named "Roslyn", [5] compiles C# source code into a .NET assembly. The compiler can also be used as a class library, which exposes types for programmatically manipulating C# source code.

An assembly, produced by the C# compiler or in some other way, can be executed on a .NET implementation. Each .NET implementation contains a runtime, which is responsible for executing code, and a base class library, which contains basic types used by .NET programs.

Runtimes of .NET implementations are usually using a just-in-time (JIT) compiler, which converts the IL for each method into machine code specific for the current instruction set just before executing that method for the first time.

In the .NET ecosystem, class libraries, which are just .NET assemblies, are commonly distributed thorough the NuGet package manager, [6] because it makes using those libraries easier. And while NuGet is primarily used for regular libraries, which are directly used by programmers in their source code, it can also be used for various kinds of special libraries, such as add-ins for general metaprogramming systems like Fody (more on these in section 1.5), or Roslyn analyzers for detecting issues with source code.

The C# language contains some basic extensibility features itself, namely virtual methods and delegates. But for more advanced use cases, it is necessary ot manipulate code in some form and the .NET ecosystem has various approaches to achieve that, including those that manipulate C# code, those that manipulate IL and those that use a custom model for representing code. Some of these approaches will be described in following sections.

1.1 Example

To demonstrate various code generation approaches, a running example of generating a simple entity class with a set of properties and having `IEquatable<T>` as an implemented interface will be used. (To make the examples shorter, the `Equals` method required to properly implement the interface will not be included.)

For example, for an entity named `Person` with properties `Name` of type `string` and `Age` of type `int`, the generated code should be similar to the one in Listing 1.

If an approach supports transforming C# code, not just generating it, the example will instead be transforming simple classes containing only fields with

```
using System;

class Person : IEquatable<Person>
{
    public string Name { get; set; }
    public int Age { get; set; }
}
```

Listing 1: Running example result

```
public static class EntityKinds
{
    // used for generating code
    public static IEnumerable<EntityKind> ToGenerate { get; }

    // used for transforming code
    public static string ToGenerateFromSource { get; }
}

public class EntityKind
{
    public string Name { get; }
    public IReadOnlyList<Property> Properties { get; }
}

public class Property
{
    public string Type { get; }
    public string Name { get; }
    public string LowercaseName { get; }
}
```

Listing 2: Running example data source

the right types and names into the form above. Such transformation is too simple to be useful in practice, but it is sufficient as a demonstration.

All examples will use the `EntityKinds` class and related types as their data source. Their relevant parts are shown in Listing 2.

1.2 Manipulating C# source code

This section describes various approaches for generating and transforming C# source code. The resulting code then needs to be compiled by the C# compiler, as usual.

1.2.1 T4

Text Template Transformation Toolkit (T4) [7] is a tool for generating text by interspersing snippets of the text to generate with fragments of C# code to control how the text is generated. The resulting text can be in any language, including C#.

```
<#@ assembly name="System.Runtime.dll" #>
<#@ assembly name="$(TargetDir)CSharpE.Samples.Core.dll" #>
<#@ import namespace="CSharpE.Samples.Core" #>
<#@ output extension=".cs" #>
using System;

<# foreach (var entityKind in EntityKinds.ToGenerate) { #>
class <#= entityKind.Name #>
    : IEquatable<<#= entityKind.Name #>>
{
<# foreach (var property in entityKind.Properties) { #>
    public <#= property.Type #> <#= property.Name #> { get; set; }
<# } #>
}
<# } #>
```

Listing 3: T4 example

T4 does not have any special way of accessing other source code, which makes it most suitable for generating code based on external data. Its text-based nature gives it flexibility, but also makes using it fairly hard, since generating C# code effectively requires writing two interleaved programs, without any help from the IDE, because T4 integration into Visual Studio is very limited.

Example

The code to generate entities using T4, as required by the running example, can be seen in Listing 3.

The example shows that a T4 file contains text blocks written in the target language (in this case, C#), but also T4 directives and control blocks, enclosed in `<#` and `#>`. T4 directives provide information to the tool, for example which assemblies to reference or what the file extension of the output file should be. Control blocks can contain C# statements, which decide how the text blocks they surround execute, or C# expressions, which parametrize these text blocks.

The example code highlights another issue with T4: indentation. It is hard to keep indentation of both the generated code and the generating code consistent, especially since any whitespace outside of T4 tags will be included in the output.

1.2.2 CodeDOM

Code Document Object Model (CodeDOM) [8] is a library for generating source code by using a language-independent object model. It is fairly easy to use, but is limited in what language features it supports, due to its language-independent nature and due to it not being updated since .NET Framework 2.0. Some of these limitations can be worked around by using string-based "snippet" objects, but using them means negating the advantages that CodeDOM has. Some examples of features it does not support are declaring `static` classes, LINQ query expressions or declaring auto-implemented properties.

Example

The code to generate entities for the running example using CodeDOM is in Listing 4.

As can be seen from the example, generating code using CodeDOM requires first building the object model. Its structure resembles the structure of a C# code file: a namespace (`CodeNamespace`) contains a class (`CodeTypeDeclaration`), which has base types and contains fields (`CodeMemberField`) and properties (`CodeMemberProperty`), which contain `get` and `set` accessors. The `get` accessor contains a `return` statement (`CodeMethodReturnStatement`), which contains an expression referencing a field (`CodeFieldReferenceExpression`). In several cases, object initializers are used to make the code to create these objects more readable. The resulting model is then converted to C# code using `CSharpCodeProvider`.

Especially notice that the code has to manually generate backing fields for properties, because CodeDOM does not support auto-implemented properties.

1.2.3 Roslyn

Roslyn [5] is the C# (and Visual Basic .NET) compiler, which can also be used as a library for manipulating C# code, including parsing, transformation and generation. Its object model was primarily designed to be used in the Visual Studio IDE, which is why it is very detailed (so it can accurately represent any source code, including erroneous or incomplete code) and also immutable (so that multiple IDE services can operate on the same model).

Roslyn contains several related Application programming interfaces (APIs) for manipulating source code, each useful in different situations:

- The `SyntaxTree` API forms the basis of Roslyn and represents only syntactic information about code. This means it can be used for just a single source file and makes it very efficient, especially when creating the `SyntaxTree` for code that contains only a small change relative to another `SyntaxTree`.

  On the other hand, no semantic information is available from this API, so for example for the expression `F(A.B)`, it is not possible to determine whether `F` is a method or a delegate, whether `A` refers to a type or a variable, or whether `B` is a field, a property, or a method group.

  The `SyntaxFactory` class can be used to create new nodes for this API.

- The `SemanticModel` class can be used to answer semantic questions about some part of a `SyntaxTree`.

  The disadvantage of using this class is that it requires a full compilation, which includes all files in a project and also all of its dependencies. It is also less efficient, especially when a change is made.

  The `SemanticModel` class surfaces semantic information in two forms:

  - The `ISymbol` API can be used to get semantic information about members declared or referenced by a piece of code.

    For example, for the expression `Console.WriteLine(42)`, this API could return the symbol for the `System.Console.WriteLine(int)`

```
var ns = new CodeNamespace();
ns.Imports.Add(new CodeNamespaceImport("System"));

foreach (var entityKind in EntityKinds.ToGenerate)
{
    var entityType = new CodeTypeDeclaration(entityKind.Name);
    entityType.BaseTypes.Add(new CodeTypeReference(
        "IEquatable", new CodeTypeReference(entityKind.Name)));

    foreach (var property in entityKind.Properties)
    {
        var propertyType = new CodeTypeReference(property.Type);

        entityType.Members.Add(new CodeMemberField
        {
            Name = property.LowercaseName, Type = propertyType
        });

        var fieldReference = new CodeFieldReferenceExpression(
            new CodeThisReferenceExpression(), property.LowercaseName);

        entityType.Members.Add(new CodeMemberProperty
        {
            Attributes = Public | Final,
            Name = property.Name,
            Type = propertyType,
            GetStatements =
            {
                new CodeMethodReturnStatement(fieldReference)
            },
            SetStatements =
            {
                new CodeAssignStatement(fieldReference,
                    new CodePropertySetValueReferenceExpression())
            }
        });
    }

    ns.Types.Add(entityType);
}

var compileUnit = new CodeCompileUnit { Namespaces = { ns } };

using (var writer = new StreamWriter("Entities.cs"))
{
    new CSharpCodeProvider().GenerateCodeFromCompileUnit(
        compileUnit, writer, null);
}
```

Listing 4: CodeDOM example

method. That symbol could then be used to find out more semantic information about that method, like the assembly it is contained in.

  - The `IOperation` API is an alternative representation of statements and expressions as a language-independent abstract syntax tree. It includes semantic information in the form of `ISymbol` objects.

- The `SyntaxGenerator` class offers an alternative, language-independent way of generating Roslyn syntax nodes. It is part of the Workspaces layer of Roslyn, which means that using it on its own requires some additional setup. `SyntaxGenerator` has a more semantic view of code, which can be easier than generating the exact syntax using `SyntaxFactory`.

  Since `SyntaxGenerator` is language-independent, it is using `SyntaxNode` in its API to represent any kind of syntax node, because `SyntaxNode` is the common base class for syntax node types in different languages. This approach makes `SyntaxGenerator` less type-safe when compared with `SyntaxFactory`, which uses specific `SyntaxNode`-derived types in its API.

Example

The code to transform entities for the running example using the `SyntaxTree` API can be seen in Listing 5.

The example first parses the input code into a `CompilationUnitSyntax`. Then it replaces each class (`ClassDeclarationSyntax`) with a modified version that has an added base type (`BaseTypeSyntax`) and which replaces each field (`FieldDeclarationSyntax`) with a property (`PropertyDeclarationSyntax`). In the end, whitespace is added to the new nodes before writing the result to a file.

Note that this code is heavily using `SyntaxFactory` to create new syntax nodes, but that type is not visible due to use of `using static`, to make the code more succinct.

Also notice how immutability makes transforming code harder by requiring the use of methods such as `ReplaceNodes` and how the level of detail leads to very verbose code, in some cases requiring even the specification of individual semicolons.

Code to transform entities for the running example using `SyntaxGenerator` can be seen in Listing 6.

Using `SyntaxGenerator` requires some setup. The first step is to create a workspace (`AdhocWorkspace`) containing a project (`Project`) containing a document (`Document`). The next step is to access the root node and semantic model (`SemanticModel`) for the document and compilation (`Compilation`) for the project. The semantic model and compilation will be used to access symbols declared in the document and referenced by the project, respectively.

The overall structure of the rest of the code is similar to the `SyntaxTree` example, except that nodes are created and modified using the `SyntaxGenerator`. Another difference is that `SyntaxGenerator` does not support auto-implemented properties, so the example has to create properties with backing fields.

Also note that `SyntaxGenerator` generates overly verbose code (for example, `global::System.IEquatable<global::Person>`), but this is counterweighted

```
var compilationUnit = ParseCompilationUnit(EntityKinds.ToGenerateFromSource);

compilationUnit = compilationUnit.ReplaceNodes(
    compilationUnit.DescendantNodes().OfType<ClassDeclarationSyntax>(),
    (_, classDeclaration) =>
    {
        classDeclaration = classDeclaration.AddBaseListTypes(
            SimpleBaseType(QualifiedName(IdentifierName("System"),
                GenericName("IEquatable").AddTypeArgumentListArguments(
                    IdentifierName(classDeclaration.Identifier)))));

        classDeclaration = classDeclaration.ReplaceNodes(
            classDeclaration.ChildNodes().OfType<FieldDeclarationSyntax>(),
            (__, fieldDeclaration) =>
            {
                var type = fieldDeclaration.Declaration.Type;
                var name = fieldDeclaration.Declaration.Variables.Single()
                    .Identifier;

                return PropertyDeclaration(type, name)
                    .AddModifiers(Token(PublicKeyword))
                    .AddAccessorListAccessors(
                        AccessorDeclaration(GetAccessorDeclaration)
                            .WithSemicolonToken(Token(SemicolonToken)),
                        AccessorDeclaration(SetAccessorDeclaration)
                            .WithSemicolonToken(Token(SemicolonToken)));
            });

        return classDeclaration;
    });

compilationUnit = compilationUnit.NormalizeWhitespace();

File.WriteAllText("Entities.cs", compilationUnit.ToString());
```

Listing 5: Roslyn `SyntaxTree` example

```
var project = new AdhocWorkspace().AddProject("MyProject", LanguageNames.CSharp)
    .AddMetadataReference(
        MetadataReference.CreateFromFile(typeof(object).Assembly.Location));
var document =
    project.AddDocument("Entities.cs", EntityKinds.ToGenerateFromSource);
var g = SyntaxGenerator.GetGenerator(document);

var rootNode = await document.GetSyntaxRootAsync();
var model = await document.GetSemanticModelAsync();
var compilation = model.Compilation;

rootNode = rootNode.ReplaceNodes(
    rootNode.DescendantNodes().OfType<ClassDeclarationSyntax>(),
    (_, classDeclaration) =>
    {
        SyntaxNode result = classDeclaration;

        result = g.AddBaseType(result, g.TypeExpression(
            compilation.GetTypeByMetadataName("System.IEquatable`1")
                .Construct(model.GetDeclaredSymbol(classDeclaration))));

        var fields = result.ChildNodes().OfType<FieldDeclarationSyntax>();

        result = result.RemoveNodes(fields, default);

        foreach (var fieldDeclaration in fields)
        {
            var type = fieldDeclaration.Declaration.Type;
            var propertyName = g.GetName(fieldDeclaration);
            var fieldName = propertyName.ToLowerInvariant();

            var field = g.WithName(fieldDeclaration, fieldName);

            var fieldAccess = g.IdentifierName(fieldName);
            var property = g.PropertyDeclaration(
                propertyName, type, Accessibility.Public,
                getAccessorStatements: new[]
                {
                    g.ReturnStatement(fieldAccess)
                },
                setAccessorStatements: new[]
                {
                    g.AssignmentStatement(
                        fieldAccess, g.IdentifierName("value"))
                });

            result = g.AddMembers(result, field, property);
        }

        return result;
    });

document = document.WithSyntaxRoot(rootNode.NormalizeWhitespace());
document = await Simplifier.ReduceAsync(document);

File.WriteAllText(
    "Entities.cs", (await document.GetSyntaxRootAsync()).ToString());
```

Listing 6: Roslyn `SyntaxGenerator` example

by being able to use another Workspace-layer service, `Simplifier`, to make the code simpler.

TODO: More obscure libraries like RoslynDOM

1.3 Manipulating IL

This section describes various libraries that can be used for generating and transforming IL code.

Since IL is primarily meant to be produced by compilers and consumed by .NET runtimes, it is not a very convenient language for programmers.

1.3.1 System.Reflection.Emit

System.Reflection.Emit [9] is a library that can be used to generate an assembly at the IL level in memory, and then either directly execute code from that assembly or save the assembly to disk.

Example

Code to generate entities for the running example using Reflection.Emit can be seen in Listing 7.

Since Reflection.Emit directly manipulates IL code, it does not use documents or compilation units. Instead, the code creates an assembly (`AssemblyBuilder`) containing a module[1] (`ModuleBuilder`), containing types (`TypeBuilder`).

At the IL level, a property is just a named grouping of methods and the code reflects that: to create the equivalent of an auto-generated property, the code creates the backing field (`FieldBuilder`), the property (`PropertyBuilder`) and the `get` and `set` accessors as methods (`MethodBuilder`). The body of each method is defined using instructions for the IL virtual stack machine. For example, the instructions used in the `set` accessor method are:

1. `ldarg.0`: Load the value of the `this` hidden argument on the stack.
2. `ldarg.1`: Load the value of the first actual argument on the stack, which contains the value to set to the property.
3. `stfld` *`field`*: Store the value at the top of the stack to an instance field *`field`* of object just below the top of the stack. Then pop both used values from the stack.
4. `ret`: Return from the method. Since the stack is empty at this point, no value is returned.

[1] Modules exist so that a single assembly could be composed of multiple separately compiled parts. This is rarely used in practice and so the vast majority of assemblies will have exactly one module.

```
var assemblyName = "MyAssembly";
var assembly = AssemblyBuilder.DefineDynamicAssembly(
    new AssemblyName(assemblyName), AssemblyBuilderAccess.Save);
var module =
    assembly.DefineDynamicModule(assemblyName, assemblyName + ".dll");

foreach (var entityKind in EntityKinds.ToGenerate)
{
    var type = module.DefineType(entityKind.Name);

    type.AddInterfaceImplementation(
        typeof(IEquatable<>).MakeGenericType(type));

    foreach (var propertyInfo in entityKind.Properties)
    {
        var propertyType = Type.GetType(propertyInfo.Type);

        var field = type.DefineField(propertyInfo.LowercaseName, propertyType,
            FieldAttributes.Private);

        var property = type.DefineProperty(propertyInfo.Name,
            PropertyAttributes.None, propertyType, new Type[0]);

        var getMethod = type.DefineMethod("get_" + propertyInfo.Name,
            MethodAttributes.Public | MethodAttributes.SpecialName,
            propertyType, new Type[0]);

        var il = getMethod.GetILGenerator();

        il.Emit(OpCodes.Ldarg_0);
        il.Emit(OpCodes.Ldfld, field);
        il.Emit(OpCodes.Ret);

        property.SetGetMethod(getMethod);

        var setMethod = type.DefineMethod("set_" + propertyInfo.Name,
            MethodAttributes.Public | MethodAttributes.SpecialName,
            typeof(void), new[] { propertyType });

        il = setMethod.GetILGenerator();

        il.Emit(OpCodes.Ldarg_0);
        il.Emit(OpCodes.Ldarg_1);
        il.Emit(OpCodes.Stfld, field);
        il.Emit(OpCodes.Ret);

        property.SetSetMethod(setMethod);
    }

    type.CreateType();
}

assembly.Save(assemblyName + ".dll");
```

Listing 7: System.Reflection.Emit example

1.3.2 Mono.Cecil

Mono.Cecil [10] is a library that can be used for generating and transforming assemblies. It was written as part of the Mono project.

The main difference between Cecil and Reflection.Emit is that Cecil can be used to read assemblies, including their IL, and to modify them, while Reflection.Emit can only be used to create brand new assemblies. Another difference is that Cecil has its own type system, independent from the type system of the .NET runtime. This means that it can be used for example to work with assemblies that target a newer version of .NET than the currently executing one, or to work with assemblies that target an incompatible .NET implementation.

Cecil does not have an example of its usage shown here. While its APIs is different from Reflection.Emit, those differences are not relevant to this work.

1.4 Other approaches

While with the approaches mentioned in previous sections, then generated code (either C# or IL) fairly closely corresponds to the generating code, other options are possible. This section describes one such library.

1.4.1 Expression trees

Expression trees, [11] contained in the System.Linq.Expressions namespace, offer another representation of code.

Expression trees were first introduced in .NET Framework 3.5, to support translating of Language Integrated Query (LINQ) queries to existing query languages, such as Structured Query Language (SQL). This initial version included only expression-like constructs and the C# language supported compiling of expression lambdas to code that creates the corresponding expression tree.

In .NET Framework 4.0, expression trees were expanded with statement-like constructs, such as blocks, assignments or loops, to support the Dynamic Language Runtime (DLR). The result is a "language" that is still expression-based, which means that even constructs such as blocks or loops can have a result. This is somewhat similar to functional languages such as F#, which also do not differentiate between statements and expressions. The C# language was not updated to support the new constructs when translating lambdas to expression trees.

An expression tree can be inspected, often in order to be translated to some query language, or it can be executed. Depending on circumstances, executing expression trees is either done by using an interpreter, or by compiling them to IL using Reflection.Emit and then executing the result.

Expression trees can only represent expressions and statements, not types or their members, which limits their usefulness when generating code. This also means the running example is not applicable to expression trees.

1.5 Metaprogramming systems

TODO: More obscure tools, especially those that work with C#

1.5.1 PostSharp

PostSharp [12] is a commercial tool for transforming built assemblies at the IL level. It focuses on aspect-oriented programming (AOP), which is the idea that cross-cutting concerns (related pieces of code that are spread over the program, such as logging or code related to thread safety) should be specified separately from the rest of the code.

An aspect is applied to the target program element, such as a method, by attaching a specific attribute to it. The attribute can also be attached to a container, such as a type or an assembly, which applies the aspect to all relevant program elements in that container. This is called "attribute multicasting".

PostSharp includes many built-in aspects and also allows specifying custom aspects. Custom aspects work by calling a user-defined method at a specific point, such as at the start of a method or before another method is called. The user-defined method can also be provided additional information about the modified method, such as its name or arguments.

This approach makes writing custom aspects easy, but it also means they are limited in what they can do and can have some performance penalty (due to allocation of the object that contains information about the modified method).

Like other tools that work at the IL level, PostSharp is also limited when it comes to changes to the shape of types, because any changes it makes will not be visible at compile time, only at runtime.

1.5.2 Fody

Fody [13] is an open-source tool for transforming the IL of assemblies. There are many published "add-ins" for Fody, usually distributed through NuGet, and custom add-ins can be written by modifying the assembly using the Mono.Cecil API (see Section 1.3.2). This makes custom add-ins hard to write, but it means they can perform any transformation. Though the limitations of IL-based tools still apply: changes to the shape of type will not be visible at compile time.

1.5.3 F# type providers

The F# language contains a feature called "type providers", [14] meant for easier access to data sources. Type providers generate types at design-time (i.e. while editing code in an IDE) based on their input parameters and on usage of the generated types. These types can be either regular types that still exist after compilation (type providers using this approach are called "generative") or their use can be transformed into some other code ("erased type providers").

Type providers use "code quotations" to express code to execute. Code quotations serve a similar purpose in F# as expression trees do in C#.

1.6 Summary

This chapter described various existing approaches for manipulating code in .NET and also several metaprogramming systems.

All of the described metaprogramming systems have severe limitations: The IL-based systems don't work well when changing the shape of a type is desired. F# type providers are a special-purpose system for accessing data sources, and also can't be directly used from C#. Because of that, a general metaprogramming system for C# that would not have these limitations would be a useful addition to the .NET ecosystem.

As for manipulating code, Section 2.1 describes in detail how an ideal approach for such a system would look like. And even if it turns out that the existing approaches are not a good fit, they can still be used for inspiration, or as part of the implementation.

2. Analysis

The goal of this work is to create a system for extending the C# language. It should be possible to use it create a wide variety of extensions, including:

- Extension similar to an F# type providers.
- Extension similar to a PostSharp aspects.
- Extension for entity types, which can generate constructors, members required for comparison and any other common boilerplate code.
- Extension that modifies how existing language feature operates, for example, improving the time complexity of recursive iterators from quadratic to linear.
- Extension that can be used to write a single method that performs numeric computation with any numeric type. This is easy to achieve with C++ templates, but impossible with C# generics, because they do not have a way of specifying operators required by the method.
- Extension that optimizes LINQ to Objects queries into efficient imperative code.
- Extension that converts an array of structures (AoS) into a structure of arrays (SoA), to improve performance of memory accesses in some cases.

TODO: More use cases from existing code generators?

Writing these extensions should be fairly easy and using extensions should not cause performance issues at design-time, build-time or run-time.

Such a system will require two major parts: an API for representing and modifying code used by extensions; and a component that drives extensions by applying their transformations at the appropriate time.

2.1 Representing code

The basic choices for representing C# code in an API are: as C# code, as IL, as some other form.

IL can be ruled out, because it is hard to use due to its low-level nature, especially when it comes to features like `async-await` (the C# compiler transforms `async` methods into state machines at the IL level).

Using a custom form would effectively require creating a new programming language (though one that does not necessarily have a textual form). The main disadvantage of doing that is that users would have to learn the new language and so it is generally the right choice only when no existing language is suitable.

This leaves the last option: using C#. This approach ensures that extension authors are already familiar with the used language, they only need to learn the API used to represent it. It also means that the output of the system will be in

C#, so existing tools for C# can be used. One disadvantage is that extensions can only use features available from C#. For example, module initializers or the `calli` IL opcode are out of reach.

Putting this all together: C# is the best choice for forming the basis of the API for representing code for this system.

Now that we know that the API will represent C# code, we need to decide how exactly it should look like:

- The API should be a .NET library.

  It would be possible to use an existing transformation language (such as Extensible Stylesheet Language Transformations (XSLT)) or create a new one. An existing language might not suit well the needs of transforming C# code and it would also require fitting C# code into the language's model (Extensible Markup Language (XML) in the case of XSLT). A new language would be unfamiliar to users and would lack tooling, at least initially. This means it would have to provide significant benefits to make creating it worth it.

  The C# language has sufficient capabilities to express the transformations required to implement C# extensions and it is guaranteed to be familiar to the target group of this system: C# programmers. This means making the API a .NET library usable from C# is the best option.

- The API should be mutable.

  Immutable persistent APIs (such as the one used by Roslyn) are useful when multiple versions of the same object need to be preserved (for example, for the "Undo" button in a code editor) or when multiple threads need access to the same object. Their disadvantage is that they make modifying objects harder: any change to a leaf of an object tree needs to be propagated to the root of the tree, creating new objects along the way.

  This system does not need to keep multiple versions of objects, but it might be useful to parallelize it. For example, when two extensions modify different sections of code, it could be advantageous to execute them in parallel. Nevertheless, because of the focus on ease of use, a mutable API is the better choice.

- The API should not reflect the syntax of C# too closely.

  In contrast with Roslyn, this API does not need to be able to represent, preserve and generate every syntactic nuance of C#, though it has to ensure that semantics of code is not changed. The basic examples of this are whitespace and comments.

  A more advanced example is the difference between declaring variables together (`int i, j;`) or separately (`int i; int j;`). The API could represent both syntactic forms the same: as a sequence of two variable declarations.

  Another example are parentheses in expressions. They are useful in the (infix) textual representation to change or emphasize the order of operations. But when representing an expression as a tree of objects, the order

of operations is clear from the structure of the tree, so parentheses are not necessary.

- The API should respect the syntactic structure of C#.

  In contrast with the previous point, the API should not be completely divorced from the syntax of C#. For example, the general structure of a simple method declaration in C# is: modifiers, return type, method name, parameters, method body. If possible, the API should follow the same order.

- The API should make common code simple.

  In the previous point, the list of elements of a method declaration was not complete: method declarations can also have attributes, type parameters and constraints. But many methods will not have these optional elements, and it should not be required to explicitly specify that a method does not have some of these elements.

  Another example are method arguments. Method argument is commonly just an expression, but it can also have a modifier like `ref` or a name. But generating a method call without these optional elements is likely going to be the most common case, so it should be simple and not burdened by the requirements of more complex cases.

- The API should be succinct.

  The structure of real code is often complex, so the API should handle generating such code. Because of this, it should avoid any unnecessary repetition, such as CodeDOM's `Code` prefix, Roslyn's `Expression` suffix or even repeated use of the `new` operator. Roslyn's `SyntaxFactory` with its `static` methods serves as a fairly good model here: when combined with `using static`, it leads to code that does not repeat itself much.

  At the same time, the API should not be too succinct by abbreviating names, for example the way the C function `strpbrk` is named. This leads to names that are hard to understand and that also violate Framework Design Guidelines. [15]

- The API should seamlessly include semantic information.

  Semantic information can be very useful, so it should be easily accessible. There shouldn't be a barrier similar to Roslyn's `SemanticModel`, where syntactic information is included in a syntax tree, but semantic information has to be accessed separately.

  On the other hand, accessing semantic information is more expensive in terms of performance than information based purely on syntax, so it might make sense to somehow discourage their use.

- The API has to be capable of handling invalid code.

  For some extensions, it will be useful if its users can write code that is not valid C#, which will then be transformed by the extension to make it valid. For example, an extension that automatically implements an interface could

require that its users specify that interface in the list of interfaces a class implements, but then omit any implementation. That is not valid C# code, but it will be filled out by the extension.

Another reason is that extensions need to work at design-time, while the code is being edited, so that auto-completion can include members produced by extensions. This is especially important for extensions similar to F# type providers, where generating new members is the reason why they exist.

Note that not all invalid code has to be handled equally well. Specifically, it is not clear how to parse or represent code that is not syntactically valid C#, such as code that attempts to use an operator that does not exist in C#. Such code still has to be handled by the API, but not necessarily consistently and it could include error nodes, or some similar representation for errors.

On the other hand, for code that is syntactically valid, but semantically invalid, such as the example of interface with no implementation mentioned above, it is clear how to parse such code and so its representation should be consistent and should not include any errors.

- The API should not be language-independent.

  Several existing APIs for representing C# code are language-independent, at least to some degree. But the goal of this work is only to make the C# language extensible, so doing this is outside its scope.

Since none of the existing APIs satisfy these criteria well, it will be necessary to create a custom API for this system.

An API that follows the principles explained above will work the best for its designed purpose: writing extensions for this system. But it could be also used for others purposes, with some limitations. For example, if such API was used to write a Roslyn analyzer, it should be able to detect semantic issues ("Was a disposable object correctly disposed?") but would likely have problems detecting syntactic or stylistic issues ("Does the code use `int` and not `Int32`?").

2.2 The system

The next step is to consider how the overall system of executing extensions and applying their transformations should work.

- The system has to have a design-time component.

  The primary purpose of some of the possible extensions mentioned at the start of this chapter is to generate code that is meant to be directly accessed by the extension's user, often generated in response to other parts of the user's code. This means that the generation has to be performed while the user is editing their code, in other words, at design-time.

- The system has to have a build-time component, which should be separate from the design-time component.

All of the mentioned possible extensions need to modify the build output, so a build-time component is clearly necessary.

And since the design-time component is likely going to be tied to a specific IDE or code editor, while the build-time component should work in a variety of situations, like building from the command line or on a build server, the two components should be separate.

- The system should support extensions with different design-time generation requirements.

  Possible extensions have various requirements on code generated at design-time and at build-time, and the system should handle all of them. These include:

  - An extension that generates different code at design-time and at build-time.

    An example of such extension is one that is similar to an erased type provider: At design-time, it generates members with no implementation, which are then accessed by the user. At build-time, the members generated at design-time don't exist and user code that uses them is transformed into some other form.

    This effectively requires writing two different transformations, one for each stage.

  - An extension that generates the same code at design-time and at build-time.

    An example is an extension similar to a generative type provider: Members are generated at design time and the same members are still used at build time.

    There is still a difference between the two stages: it is not necessary to generate implementation of generated members at design-time, which is especially useful since design-time transformations are more time-sensitive. But it shouldn't have be required to write two similar transformations for this.

  - An extension that generates no code at design-time, only at build-time.

    An example is an extension similar to an aspect: The extension is activated by attaching an attribute to a code element. The attribute doe not change, so it does not have to be generated and can come from a regular library. This means that no code has to be generated at design-time. At build-time, the relevant code is then transformed based on what the aspect does.

- The system should regenerate only code that depends on modified code at design-time.

  Performance of the design-time component is important, because it directly affects user experience when editing code that uses extensions, especially when it comes to auto-completion.

  To help with that, we can take advantage of the fact that when the user is editing their code, they usually only change one piece of it at a time. And

since parts of an extension's transformation usually only depend on specific pieces of user code, it should be possible to execute only the parts of the transformation that depend on changed pieces of user code.

Another reason why this should be done is that extensions can affect performance of the whole system in unpredictable ways and limiting how much extension code runs also limits that unpredictability.

Doing this might require extending the API of the system.

- The system should make experimenting when creating extensions easy.

  For example, if the system included the API suggested in the previous point, using it makes the extension more efficient but also more complicated. Because of that, use of this API should be recommended, but optional. This way, experimenting with writing extensions or creating personal extensions is simple thanks to the simple API, while production extensions can be efficient thanks to the complex API.

- The system should allow distributing extensions through NuGet.

  NuGet is an established distribution channel for regular .NET libraries, and also for other kinds of libraries, like Roslyn analyzers or Fody add-ins. This makes NuGet a good fit for distributing extensions for this system.

  This also effectively implies that extensions should be distributed as .NET libraries. While NuGet can work for other kinds of artifacts, it works best for .NET libraries.

- The system should allow extensions to report errors and warnings about code.

  Many extensions are likely going to have ways of using their API (generated or not) in ways that are suspicious or outright incorrect. The system should let extensions report these issues to the user, including identifying the problematic part of their code.

  As a side-effect, it would be possible to write an extension that does not perform any transformations, it only reports errors or warnings. Such extension would serve the same purpose as a Roslyn analyzer and would have similar limitations than those mentioned at the end of the previous Section.

3. Design

Before starting actual design of the system, its name should be decided. This name would be used in names of namespaces, assemblies, NuGet packages and so on, so it should fit well with their requirements and conventions. The name should also be reasonably unique, easy to remember and not too long. The name chosen based on these principles is "CSharpE", meaning "C#, extensible".

As explained in the previous chapter, this system has two main tasks: representing code and transforming code. This means it is natural to split the project into two main parts: `CSharpE.Syntax` and `CSharpE.Transform`, respectively.

3.1 CSharpE.Syntax

The `CSharpE.Syntax` namespace contains all the types necessary for representing and modifying C# code starting from the project level and going down all the way to the expression level. There is no representation for solutions, because extensions work at the project level, which means solutions are not necessary.

3.1.1 Example

Before explaining details about the design of this namespace, it might be useful to see an example of its usage. Listing 8 shows how the running example from Section 1.1 could be implemented using this API. Notice how the code is very short, when compared with the previously shown examples from Chapter 1, without resorting to a custom language that mixes two programs, like T4 does. This is thanks to following the guidelines from Section 2.1.

Specifically, what the code does is to create a project (`Project`) containing one source file (`SourceFile`) that contains the initial code. Then it finds classes (`ClassDefinition`) in the project and for each of them, adds `IEquatable<T>` to the list of base types and also changes all its fields (`FieldDefinition`) to auto-implemented properties (`PropertyDefinition`).

The rest of this chapter describes the API in detail.

3.1.2 General principles

There are some rules that apply though all levels of this API:

- Types in this API are regular mutable classes.
- Types that represent nodes in the C# syntax tree inherit from the common base class `SyntaxNode`. This includes most types from the source file level down.

  A syntax node can have only one parent node, to make sure the syntax tree is actually a tree and so that mutating a node does not affect another, seemingly unrelated part of the syntax tree. But this parent node is not exposed in the API, for reasons explained in Section 3.2.2.

```
var project = new Project(new SourceFile(
    "Entities.cs", EntityKinds.ToGenerateFromSource));

foreach (var classDefinition in project.GetClasses())
{
    classDefinition.BaseTypes.Add(
        TypeReference(typeof(IEquatable<>), classDefinition));

    foreach (var field in classDefinition.Fields)
    {
        classDefinition.AddAutoProperty(Public, field.Type, field.Name);
    }

    classDefinition.Fields.Clear();
}

File.WriteAllText("Entities.cs", project.SourceFiles.Single().GetText());
```

Listing 8: CSharpE.Syntax example

Syntax nodes can be deep cloned by calling the `Clone` method, which is a generic extension method. It is that way to avoid having to cast its result to the correct type, which would be necessary if `Clone` was a simple instance method on `SyntaxNode`. Syntax nodes are also cloned instead of assigning a new parent node, to maintain the tree shape.

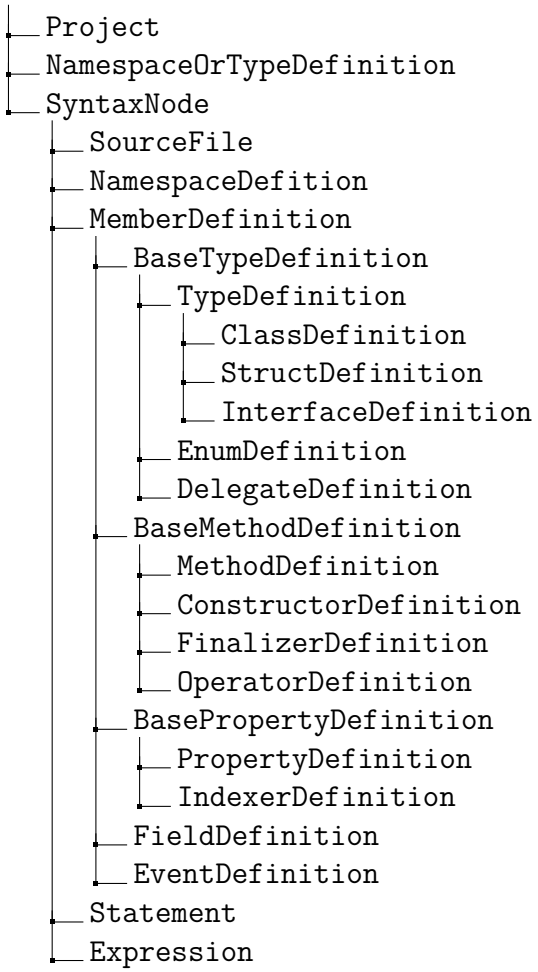
- Collections of nodes are usually exposed as properties of type `IList<T>`. This interface is the most flexible out of the commonly used collection interfaces in .NET. Using an interface means that the user is shielded from the implementation detail of which specific collection type is used.

  Using this interface, which is implemented by commonly used types like arrays or `List<T>`, also means that collection properties can have easily usable setters. For example, to set the body of a method to a specific sequence of statements, one could use code similar to the following: `method.Body.Statements = new Statement[] { ... };`.

  For convenience, some collections are also exposed on higher levels as methods. For example, `TypeDefintion` contains the `Methods` property, while `SourceFile` and `Project` contain the `GetMethods` method, which returns methods from the whole file or project, respectively. Such methods return `IEnumerable<T>`, because it does not make sense to for example add a method directly to a file or a project, it has to be added to a specific type.

- The API includes implicit conversion operators when appropriate. Specifically, they can be used to convert from a definition to a reference (e.g. from `TypeDefinition` to `NamedTypeReference`) or from a node to a simple wrapper for that node (e.g. from `Expression` to `ExpressionStatement`).

  Using implicit conversions makes code shorter, but also harder to understand, because it is an operation that is not visible in the code. For this reason, all implicit conversion operators have an alternative form, usually a constructor of the target type.



Listing 9: Inheritance hierarchy of commonly used types in the `CSharpE.Syntax` namespace

- There is a `SyntaxFactory` type, which exists to make creating syntax nodes more succinct, when combined with `using static`. For example, it means that to use the `this` keyword, it is possible to write just `This()`, instead of `new ThisExpression()`.

Listing 9 shows inheritance hierarchy of the `CSharpE.Syntax` namespace.

3.1.3 Projects

At the top of this API is the `Project` class, which represents a collection of C# source files and library references. It also contains helper methods for accessing types from all files within a project, for extensions that do not care about which file contains which type.

The `Project` class is also point of interoperation between this API and Roslyn: `Project` can be constructed from a `CSharpCompilation` and it also exposes a `CSharpCompilation` as a property.

3.1.4 Source files

Each C# source file in the project is represented as an instance of the `SourceFile` class. A source file has name, text and a list of members, which are namespace and type definitions.

The obvious object-oriented way to model this list would be to have a common base class shared by the namespace definition class and the type definition class. The problem with this is that types can be members of other types, while namespaces cannot. So, we would want type definition to inherit from the member definition class (along with other kinds of type members), and namespace definition to not inherit from that class. But this is not possible, because .NET does not allow multiple inheritance of classes.

There are several options of how to resolve this:

- Make the common base class of namespace definition and type definition into an interface, since multiple inheritance of interfaces is allowed. This interface would not be very useful on its own, since namespace and type definitions are not very similar and generally require different processing.
- Make namespace definition inherit from the member definition class. This would allow adding namespace definitions as members of types, which is not valid C#, so it is undesirable.
- Don't have namespace definitions in the syntax tree at all, instead the namespace of a type definition is surfaced as a property. This is how namespaces are represented in IL and Reflection. The problem with this is that deviates from the syntax of C# too much, which could be confusing to users.
- Use a different class for representing nested type definitions. This way, there is no issue with multiple inheritance, because each base class would be inherited by a different class. The problem here is that users will probably expect that nested types behave the same as regular types, since both have the same syntax in C#.
- Instead of a common base type, use a discriminated union. The biggest issue with this approach is that it is not commonly used in object-oriented design and so it might be unfamiliar to C# programmers and it also would not fit well with the rest of this object-oriented API.

The option chosen from the above was to use discriminated union `struct` called `NamespaceOrTypeDefinition`, because it fits the best with the expected usage pattern of these types, where nested types and regular types are handled the same, while namespaces and types are handled in separate code paths.

Notice that `using` directives are not exposed in the API at all, because they are managed automatically. This makes the API easier to use, at the cost of preventing users from choosing which syntax should be used, which is consistent with the principles outlined in the previous chapter.

3.1.5 Types

The types that can be defined in C# are classes, structs, interfaces, enums and delegates. Classes, structs and interfaces are very similar in that all three can be generic, have a list of base types and have various members. Also, especially when it comes to classes and structs, it could make sense fairly often to manipulate them in the same way.

This means that a reasonable design would be to have the types for classes, structs and interfaces inherit from a common base class and this base class, along with the types for enums and delegates, should inherit from another base class. The problem with this design is naming: there is no established name that would apply to classes, structs and interfaces, but not to enums and delegates. For this reason, the names chosen for the two base classes are `TypeDefinition` and `BaseTypeDefinition`.

For a `TypeDefinition`, all its members are contained in the `Members` list, while various kinds of members like fields or methods are also contained in their own lists (for example, `Fields` or `Methods`). These smaller lists are kept synchronized with the main list of members. This means these lists effectively act as filtered views on the main list.

To make adding new members easier, `TypeDefinition` also contains methods like `AddFields`. For example, consider the following code:

```
1 var field = new FieldDefinition(...);
2 type.Fields.Add(field);
```

By using the `AddFields` method, that code can be simplified to:

```
1 var field = type.AddField(...);
```

3.1.6 Members

Class, struct and interface definitions can contain various kinds of members, namely fields, methods, properties, events, indexers, operators, constructors, finalizers (also known as destructors) and nested type definitions. Not all kinds of members are valid for all three kinds of types, but since invalid members might be useful to some extensions, the API still allows them.

All kinds of members can have modifiers. While in source, member modifiers can be defined in different order (for example, both `public static` and `static public` are valid modifiers for a method), this order does not make a difference. For this reason, this API represents all modifiers using a single flags enum, `MemberModifiers`.

Because manipulating flags enums using bitwise operators can be cumbersome, the API also includes helper read-write properties for most valid modifiers for each kind of member. The exception to this are access modifiers. Because a member can have only one kind of declared accessibility (which includes all the access modifiers on their own and also the combinations `protected internal` and `private protected`), access modifiers are surfaced as a read-write property named `Accessibility`, along with a read-only property for each kind of declared accessibility.

Even though the list of kinds of members above might make it seem like the mapping between syntactic forms of members from the C# specification and types in this API should be obvious, it is not. The cases that are not obvious are:

- Constants, fields and field-like events can define more than one member with each declaration, for example, `private int x, y;`. With considered designs, this ability makes processing all declarations of these kinds significantly harder, even those that declare just one member. For this reason, each member defined in this way is actually represented as a distinct instance of the appropriate type. For example, the previously shown declaration would be represented as two instances of the `FieldDefinition` type.

- The specification lists constants separately from fields. But since constants are very similar to fields with the `const` modifier, that is how they are represented: both are `FieldDefinition`, the difference is only in modifiers. This also makes changing a field to a constant or vice versa easier.

- The specification lists two syntactic forms of events: field-like events and events with accessors. Since both define the same kind of member, they are both represented as `EventDefinition`.

  This is made easier by splitting a single declaration with multiple definitions into separate instances, as mentioned before, because otherwise the same type would have to represent quite distinct values: a field-like event declaration that has no accessors, but could define more than one event; and a declaration of an event with accessors, which always defines exactly one event.

- The specification lists three syntactic forms of operators: unary operators, binary operators and conversion operators. It would be possible to have a separate type for each form, but a simpler solution is to have just one type, `OperatorDefinition`, which represents all three forms. An `OperatorDefinition` then has a kind, which is `Implicit` or `Explicit` for conversion operators, or the name of one of the overloadable unary or binary operators (for example, `Addition` or `Xor`).

- The specification lists instance constructors and static constructors separately. But since `Static` already exists as a member modifier for other kinds of members, it could be confusing if it did not work for constructors. For this reason, both instance and static constructors are represented as `ConstructorDefinition`.

- The Microsoft C# specification calls the member that is invoked before an instance is garbage collected "destructor". But the Ecma C# specification[1] and the official documentation [16] both call this member "finalizer", so that is the name used here.

[1] Quoting from [17]:

> In an earlier version of this standard, what is now referred to as a "finalizer" was

Another set of decisions to make are about the inheritance hierarchy of member definitions:

- Classes for all kinds of member definitions derive from a common base class, `MemberDefinition`. This includes type definitions, to support nested types, as has been described in previous sections.
- Methods, constructors, destructors and operators all have parameters and a body, so they inherit from the `BaseMethodDefinition` class. This could make processing method-like definitions easier.
- Properties and indexers both have a type and also `get` and `set` accessors, so they inherit from `BasePropertyDefinition`. Events also have a type and accessors, but they are a different set of accessors (`add` and `remove`), so they are not included.

TODO: Bodies

3.1.7 Statements

3.1.8 Expressions

3.1.9 References

3.2 CSharpE.Transform

Now that the API for representing and modifying code has been designed, it is time to decide how is the system going to transform a project for some extension. Per Section 2.2, extensions are distributed as .NET libraries. This means the system will need some way to recognize what transformations an extension wants to perform and then execute them.

A reasonable way to do this is to have an interface that is implemented by each transformation. The system would then create an instance of the type (or types) that implements this interface and call a method on it whenever the transformation needs to be performed.

As has been explained before, the transformations that need to be performed can be different at design time and at build time. Also, different extensions will have different relationships between the two transformations. To fulfill these two requirements, the interface will include a parameter that specifies which transformation should be performed and there will also be abstract classes that hide this parameter for transformations that do not need it. This way, full flexibility of using an interface is maintained, while recommended patterns are communicated using the abstract classes.

called a “destructor”. Experience has shown that the term “destructor” caused confusion and often resulted to incorrect expectations, especially to programmers knowing C++. In C++, a destructor is called in a determinate manner, whereas, in C#, a finalizer is not. To get determinate behavior from C#, one should use `Dispose`.

```
public interface ITransformation
{
    void Process(Project project, bool designTime);
}

public abstract class Transformation : ITransformation
{
    public abstract void Process(Project project, bool designTime);

    protected static Statement NotImplementedStatement { get; }
}

public abstract class SimpleTransformation : Transformation
{
    protected abstract void Process(Project project);
}

public abstract class BuildTimeTransformation : Transformation
{
    protected abstract void Process(Project project);
}
```

Listing 10: Simplified API of types used to implement transformations

Listing 10 shows the API of this interface (`ITransformation`) and the related abstract classes:

- The base class `Transformation`, which is a convenient location for helper members that are going to be useful in many transformations. Specifically, the `NotImplementedStatement` property should be useful in most transformations that have a design-time component, as the body of generated members.
- The `SimpleTransformation` class, which can be used for transformations that behave the same at design-time and at build-time.
- The `BuildTimeTransformation` class, which can be used for transformations that do not do anything at design-time, for example, aspects.

Listing 11 shows how the running example from Section 1.1 could be implemented as a transformation. Notice that it uses one of the aforementioned abstract classes and that the body of the method is the same as the main part of Listing 8.

3.2.1 Making transformations efficient

A much more complicated question is: how to make design-time transformations efficient, by regenerating only code that depends on code modified by the user? As can be seen from the previous example, transformations are often structured around `foreach` loops over syntax nodes: the transformation applies for each class, or for each type with an attribute, or for each method. And this includes `foreach` loops that are hidden by convenience methods from `CSharpE.Syntax`. For example, consider the following code iterating over all methods in a project:

```
public class EntityTransformation : SimpleTransformation
{
    protected override void Process(Project project)
    {
        foreach (var classDefinition in project.GetClasses())
        {
            classDefinition.BaseTypes.Add(
                TypeReference(typeof(IEquatable<>), classDefinition));

            foreach (var field in classDefinition.Fields)
            {
                classDefinition.AddAutoProperty(
                    Public, field.Type, field.Name);
            }

            classDefinition.Fields.Clear();
        }
    }
}
```

Listing 11: CSharpE.Transform simple example

```
foreach (var method in project.Methods())
{
   ...
}
```

The above code is effectively the same as the following code, which does not use convenience methods:

```
foreach (var file in project.SourceFiles)
{
    foreach (var type in file.GetTypes())
    {
        foreach (var method in type.Methods)
        {
            ...
        }
    }
}
```

This, combined with the fact that a programmer editing their code usually focuses at a single higher-level syntax node (like a method or a class) at a time, makes `foreach` loops ideal to decide whether transformation code should be executed again: the system could make this decision for each iteration of a `foreach` loop, based primarily on whether the syntax node that is being processed by that iteration changed.

Bu the regular `foreach` loop does not offer sufficient flexibility for the kind of operations that will be required to implement this "smart" `foreach` loop, so an alternative has to be considered.

One option would be to create a transformation for writing transformations: the author of a transformation writes a regular `foreach` loop, which is then translated into a smart loop. The problem with this approach is that it hides what should be explicit: as explained in detail below, there are significant differences

```
public class EntityTransformation : SimpleTransformation
{
    protected override void Process(Project project)
    {
        Smart.ForEach(project.GetClasses(), classDefinition =>
        {
            classDefinition.BaseTypes.Add(
                TypeReference(typeof(IEquatable<>), classDefinition));

            foreach (var field in classDefinition.Fields)
            {
                classDefinition.AddAutoProperty(
                    Public, field.Type, field.Name);
            }

            classDefinition.Fields.Clear();
        });
    }
}
```

Listing 12: Example of CSharpE.Transform smart `foreach` loop

between the behavior of a regular `foreach` loop and a smart loop, which should not be hidden from the transformation author.

Instead, a method with a lambda parameter will be used, similar to the `Parallel.ForEach` method in .NET. [18]

To make this more concrete, Listing 12 shows how the smart `foreach` loop could be used in the running example. Notice that the outer `foreach` loop from Listing 11 was replaced with a call to the `Smart.ForEach` method, with a lambda serving as the loop body. Why the inner loop was not similarly changed will be explained at a later point.

In general, how this works is that each loop iteration has its own inputs and outputs. Inputs are the syntax nodes and other data that the iteration has access to. Outputs are any changes made to those syntax nodes and also any data it returns (while a regular `foreach` loop cannot return anything, a `foreach`-like method can).

When an iteration of the loop is executed for the first time, its body is invoked as if it was a regular `foreach` loop, but at the same time, its inputs and outputs are recorded. When it is executed again, the new inputs are compared with the recorded ones. If they match, instead of invoking the loop body, the recorded outputs are used. This way, if only a small part of the input changes, there is a good chance that only small part of the transformation will have to be executed again.

As an example, consider a project with two files, each of which contains two classes and a transformation that uses a smart `foreach` loop over the project's classes. Since the loop over classes in a project includes a hidden loop over files in the project, the first time this transformation is ran, an iteration of the first loop will be executed for each of the two files and an iteration of the second loop will be executed for each of the four classes.

If the second class in the second file is modified and the transformation is ran

```
(TransformProject, , transform)
(SourceFile, File1.cs, transform)
(ClassDefinition, Class1A, transform)
(ClassDefinition, Class1B, transform)
(SourceFile, File2.cs, transform)
(ClassDefinition, Class2A, transform)
(ClassDefinition, Class2B, transform)

(TransformProject, , transform)
(SourceFile, File1.cs, cached)
(SourceFile, File2.cs, transform)
(ClassDefinition, Class2A, cached)
(ClassDefinition, Class2B, transform)
```

Listing 13: Log output for running a transformation twice, with a change between the runs

again, the first iteration of the first loop will not be executed, because nothing in the first file changed. The previously recorded outputs will be used for this iteration. The second iteration will be executed, because the second file changed. The iteration for the first class in the second file will not be executed, because the code of this class did not change. The only class for which any code from the transformation will be executed is the one that changed: the second class of the second file.

Listing 13 shows the output of internal logging for this scenario. Each line represents a section of code to be executed. The first entry on each line is the name of the type of the object that is being processed. The second entry is the name of the object (empty in the case of a project). The last entry indicates whether the section of code was actually executed: `transform` means that it was executed, `cached` means that it was not executed and that its recorded outputs were used.

3.2.2 Smart loop details

When it comes to designing how exactly the smart `foreach` loop should look like, there are several considerations:

- The system assumes that code in a loop iteration body is deterministic and free of unrecognized side-effects.

  For smart loops to work correctly, the output of each loop iteration has to depend only on its inputs and all its outputs have to be recognized by the system. Otherwise, when the recognized inputs stay the same, the iteration is not re-executed, and the end result is different than what it would be without a smart loop.

  This does not mean non-determinism or side-effects are completely forbidden in transformations, but it does mean they are severely limited. Some examples:

  - If an iteration needs access to the current date, it should not read the `DateTime.Today` property itself. Instead, its value can be passed as

an input.

- If an iteration logs what it does to a file, it might be acceptable that the log file is only updated when the inputs change.
- If an iteration updates some global cache, then that is technically a side-effect. But if that cache is only used to make the code more efficient and no code relies on it for correctness, then this side-effect does not cause any issues.
- If an iteration uses a randomized algorithm, the fact that the output of the algorithm could change with each execution is generally not a positive feature. In this case, skipping re-execution should be acceptable.
- Mutating the syntax node that is being processed by the iteration, including its child nodes, is explicitly allowed. This is because any changes to that node are recognized by the system and are re-applied even if execution of the iteration is skipped.

Because nondeterminism and unrecognized side-effects can sometimes be desirable, and because .NET does not have a good way of recognizing them, the system does not have any mechanism of preventing them.

Also note that nondeterminism might be undesirable in a transformation, even when ignoring its effects on smart loops. This is because a transformation can decide what code is valid and how the code behaves when executed. So, code that compiles and works correctly now could stop compiling or it could change its behavior in the future, which is generally undesirable.

- Access to syntax nodes has to be controlled.

  When some syntax node is accessed by a loop iteration, and this syntax node is changed between two executions of that iteration, the iteration has to be re-executed, because that change could alter its output. While it would be possible to track which syntax nodes are accessed by an iteration, the system described in this work does not attempt to do so, on the assumption that it is not necessary to achieve sufficient performance for design-time transformations.

  Instead, whenever any syntax node accessible by a loop iteration changes, that iteration is re-executed. As a consequence of this, syntax node objects do not have parent references, as has been pointed out in Section 3.1.2. If such references did exist, the whole file or even the whole project would be accessible from any syntax node, which means even a small change would cause re-execution of large amounts of code.

  Instead of providing no parent references whatsoever, another option would be to have parent references on all node types, but prohibit accessing "dangerous" parents at runtime (attempting to do so could result in throwing an exception or returning `null`). But because this could be confusing to users and because parent references are not necessary, this option was not chosen.

Another consequence of these node accessibility rules is that care has to be taken about which other nodes, apart from the one being processed by the loop iteration, are accessible. This is considered along with other kinds of input in the next point.

- All data that is passed in has to be tracked.

  The system has to understand all inputs of a loop iteration. This includes the syntax node that is being processed by the iteration, but also any other data. For that data, the system has to:

  - understand when they change, so that it can correctly decide when to re-execute the loop,
  - ensure loop iterations do not mutate them, which would be considered an unrecognized output,
  - deep clone them, so that further mutations after the smart loop do not affect following executions.

  For these reasons, the system strictly controls which data types are allowed as additional inputs. The allowed types are: primitive types (such as `int` and `bool`), `string`, delegates without closures, syntax nodes, and also tuples, arrays and lists of allowed types. This set of types should be sufficient for most use cases, but if it turns out it is not, it can be easily extended in the future.

  The natural way of passing additional data into a lambda is by directly accessing variables from the outer scope. When such lambda is compiled, any variables from the outer scope that it accesses are stored in a closure object, that then becomes part of the delegate that represents the lambda.

  The system could attempt to recognize this closure object as part of the inputs to a smart loop, but this approach has several issues:

  - Depending on how exactly the compiler decided to form the closure object, it could include more variables than necessary.

    For example, consider the following code:

    ```
    1  int a = 1, b = 2;
    2
    3  SomeMethod(() => a);
    4  SomeMethod(() => b);
    ```

    The current version of the compiler creates a single shared closure object for both lambdas, which means inspecting the closure object for either lambda will reveal fields for both local variables.

    For smart loops, this would mean that the system would have to assume that all fields in the closure object are inputs, which would lead to unnecessary re-executions when a variable is included in the closure object, but is not actually used by the lambda.
  - The exact shape of the closure object is an implementation detail of the compiler, which the system would have to understand.

There is no specification that governs what shape closure objects created by the compiler should have. The compiler can behave differently in different situations and its behavior can also change between versions.

The system would need to have a fairly deep understanding of this behavior, so that it could understand when the data changes, ensure it is not mutated by loop iterations and deep clone it, as explained previously.

– It is not explicit.

In most cases, it is not important to understand which variables from the outer scope are accessed by a lambda in regular C# code, which is why C# does not have any built-in way of determining or controlling this (unlike for example C++, where the capture list has to be explicitly specified for each lambda).

But this is different for the lambda that forms the body of a smart loop, because each additional accessed variable could be the cause of re-execution, which would make understanding which variables are accessed by a lambda important.

For these reasons, passing additional data to a smart loop through closure objects is not allowed. In fact, the system checks that the lambda passed as the body of a smart loop does not access any variables from the outer scope and throws an exception if it does. This still relies on implementation details of the compiler,[2] but to a lesser degree, so it should be less brittle than allowing passing data through closure objects.

Instead, additional data is passed as arguments to the `Smart.ForEach` method, and accessed by the loop body as additional parameters to the lambda. One disadvantage of this approach is that it effectively requires having two different names for the same variable (one outside the loop, and one inside), because C# does not allow variable shadowing within methods.

- All data that is passed out has to be tracked.

Regular loops in C# do not return values, instead, they often mutate some object from the outer scope (for example, an iteration could call `Add` on a `List<T>` that is declared outside the loop). Since this is not allowed according to the rules described in the previous point, an alternative approach that can be more easily controlled by the system would be very useful.

The approach used by the system is to allow the lambda that represents the body of the loop to return a value. The whole loop then returns a list of these values (specifically, `IReadOnlyList<T>`), one for each iteration. When an iteration is not re-executed, the previously returned value is used again. To make sure further changes to returned values do not affect following

[2]The representation of lambdas that do not access any variables from the outer scope did indeed change in the past. With the compiler for C# 5.0 or older, the closure object for such lambdas was `null`. With the compiler for C# 6.0 or newer, the closure object is instead an instance of a compiler-generated class with no instance fields. [19] The system accepts both approaches.

executions, the values returned from loop iterations are deep cloned. For this reason, they also have the same limitation on allowed types as input values.

- The system has to understand the collection that is being iterated.

  To efficiently re-execute a smart loop, the system has to have a good understanding of what changed in the collection since the last execution. And because smart loops are often nested, either explicitly, or implicitly by using convenience methods that bypass one or more levels of syntax nodes (such as the previously mentioned `project.Methods()`), it is not enough to determine when an item in a current version of the collection is exactly the same as an item in the previous version: it is also important to recognize when a current item is similar to an item from the previous version, so that results can be reused for the parts of the item that did not change.

  Because computing these kind of differences for arbitrary collections is not trivial and generally should not be necessary in transformations, the system only allows performing smart loops on collections provided by the system. Since these collections satisfy some specific conditions (for example, a collection that only contains syntax nodes from the same file in source code order), computing their differences is fairly easy and the results should be quite accurate.

  Also, collections that bypass levels of syntax nodes, which are returned by convenience methods, have to be understood by the system, so that a smart loop over one of them behaves the same as multiple nested smart loops, one for each level of syntax nodes. This way, determining which code does not have to be re-executed can happen at larger granularities.

  An alternative design, which would avoid the need for recognizing these special collections, would be to have a smart loop method for each collection on each type of syntax node. For example, consider the following code:

```
1 Smart.ForEach(project.GetClasses(), lambda);
```

  With this alternative design, it would be instead:

```
1 project.ForEachClass(lambda);
```

  While this syntax might look appealing at first, the problem with it is that it would significantly increase the API surface: the `Smart.ForEach` method has several overloads (for varying number of arguments passed to the lambda and for returning a result collection) and this design would require adding those overloads for every collection on every type of syntax node. For this reason, the alternative design was rejected.

- The smart loop methods should not be extension methods.

  According to Framework Design Guidelines, extension methods should only be used when they work for every implementation of an interface. [20] Since smart loops only work for collections provided by the system, making them extension methods would be a violation of the guidelines.

```
public class EntityTransformation : SimpleTransformation
{
    protected override void Process(Project project)
    {
        Smart.ForEach(project.GetClasses(), classDefinition =>
        {
            classDefinition.BaseTypes.Add(
                TypeReference(typeof(IEquatable<>), classDefinition));

            var fieldsList = Smart.ForEach(classDefinition.Fields,
                field => (field.Type, field.Name));

            foreach (var field in fieldsList)
            {
                Smart.Segment(classDefinition, field, (f, classDef) =>
                    classDef.AddAutoProperty(Public, f.Type, f.Name));
            }

            classDefinition.Fields.Clear();
        });
    }
}
```

Listing 14: Example of CSharpE.Transform smart segment

3.2.3 Smart segment

Now that we understand the limitations of smart loops, it should be clear why the second `foreach` loop in Listing 12 cannot be a smart loop: it iterates over fields of a class, which means an iteration of a smart loop would only be allowed to mutate the field it is processing, when it needs to mutate the class itself by adding a property to it.

Because code like this, where a member is generated based on another existing member, is expected to be common, CSharpE.Transform contains a special method just for this purpose: It is called `Smart.Segment` and it creates a segment of code that can add members to a type, but is strictly limited when it comes to interacting with the type in any other way. Specifically, this means that the code in such a segment does not depend on members of the type, which means it does not have to be re-executed when an unrelated member changes.

Listing 14 shows how `Smart.Segment` can be used in the running example. Notice that the original `foreach` loop has been changed into a smart loop that reads relevant data from fields and a regular `foreach` loop that adds properties through `Smart.Segment`.

3.3 User experience

Another aspect of the system that should be considered is the experience of both creating an extension and using one or more extensions when writing code.

Because a CSharpE extension is a regular .NET library that references the CSharpE.Transform library and implements the transformation interface, it is created using the same tools as any other .NET library. And just like most .NET

libraries, extensions are distributed as NuGet packages and can use any supported distribution channel, including NuGet.org.

The situation is more complicated for code that wants to use extensions. First, consider file extensions. CSharpE could require a custom file extension (like `.cse`) for source files that have transformations applied to them. But that means fully adopting CSharpE in a project would require renaming all source files. Also, it could lead to a situation where some files in a project are using CSharpE and some are not, which could be confusing. For these reasons, CSharpE should use the same file extension as C#: `.cs`.

Second, build-time versions of extension transformations have to be executed whenever user code that uses extensions is built. This includes the user choosing to build their code from an IDE, but also building on a build server, possibly as part of a Continuous integration (CI) process. In both cases, the code will be built using MSBuild, which means a reasonable choice is to take advantage of its extensibility options by creating a custom "task" that will be executed before the build process invokes the C# compiler. This custom task can be distributed through NuGet, making it easy to install alongside extensions.

Third, design-time versions of transformations have to be executed while the user is editing their code in an IDE and the experience should be as close as possible to editing regular C# code. Because every IDE and code editor has their own mechanism for extending it, only Visual Studio will be supported.

Fourth, it should be possible to use debugging while developing extensions and code that is using extensions. Extension authors will want to debug extensions themselves and also user code after the build-time version of a transformation has been run. Extension users would likely prefer to see only the code they wrote, while code after build-time transformations is being debugged.

Debugging extensions is complicated by the fact that they run inside MSBuild and Visual Studio. To debug them, advanced debugging techniques have to be used, such as manually specifying debug executable, attaching the debugger to a running process or using `Debugger.Break();` [21] to launch the debugger when the transformation is executed. This is not ideal, and even though one of the goals of this system is to make developing extensions as easy as possible, it is likely extensions will be mostly developed by more experienced developers, so these hurdles should be acceptable.

Debugging user code after build-time transformations works thanks to the MSBuild custom task. This is because the task runs before the C# compiler, which means the compiler only sees the transformed code and so it points to that in debugging symbols.

Seeing only user code while debugging would be useful, but it is not necessary, so it has not been implemented.

TODO: conclusion

4. Implementation

As has been explained before, the implementation should be a .NET library usable from C#. While it would be possible to write such a library in another .NET language, C#, as a general-purpose programming language, is suitable for this task, so it is the language used in the implementation.

One of the principles of the design of the system has been a focus on performance, especially when it comes to limiting executing the code of transformations. The implementation also sometimes considers performance, but generally speaking, maintainability and readability of code take precedence, especially at the method level. Because some of the code written this way might be performance-critical, the intention is to use profiling and optimize the found bottlenecks, but this has not been done in the current version.

The implementation of the system is composed of four main projects:

- `CSharpE.Syntax`, for representing code,
- `CSharpE.Transform`, for transforming code,
- `CSharpE.Transform.VisualStudio`, which supports using extensions at design-time in Visual Studio,
- `CSharpE.Transform.MSBuild`, which supports using extensions at build-time in MSBuild.

4.1 CSharpE.Syntax

The most complicated part of the job of `CSharpE.Syntax` is to convert from C# source code to CSharpE code representation and vice versa. To help with this, we can use Roslyn. Thanks to Roslyn, it is only necessary to write code that converts between the Roslyn representation and the CSharpE representation, which is much easier. Also, by using Roslyn, we use the same code as the C# compiler, which means there is no chance of introducing parsing bugs.

Because CSharpE syntax nodes and Roslyn syntax nodes often have very close correspondence and because transformations often access only some parts of the syntax tree, a CSharpE syntax tree that is created from a Roslyn syntax tree acts as a lazy wrapper over it: CSharpE nodes are created from the corresponding Roslyn nodes only as necessary. In other words, when a CSharpE node is created from a Roslyn node, it stores the Roslyn node. When one of its child nodes is then accessed for the first time, it is created from the corresponding child of the Roslyn node.

Syntax nodes can also have properties that are not child syntax nodes and are not lazy. For example, the property `string Name` of `TypeDefinition` is one.

After a CSharpE syntax node is created, it can then be modified by the user. Eventually, it will need to be converted back to C# source code, which is once more done through Roslyn nodes: CSharpE nodes implement the internal interface `ISyntaxWrapper<TSyntax>`, which can be seen in Listing 15. The single

```
internal interface ISyntaxWrapper<out TSyntax>
{
    TSyntax GetWrapped(ref bool? changed);
}
```

Listing 15: Declaration of the ISyntaxWrapper interface

method of this interface, `GetWrapped`, is used to retrieve an up-to-date version of the Roslyn node (`TSyntax`) for a CSharpE node. The `changed` parameter is used by the `GetWrapped` method of the parent node to detect whether the current node changed since the parent called the `GetWrapped` method of the child node last. Any other caller is required to pass a reference to `null` for the parameter.

Another option would be to notify ancestor nodes whenever a node is modified. This way, a node that has not changed would not have to be inspected for changes, which could be more efficient. Though this approach is more complicated and so it has not been implemented.

Listing 16 shows how a typical implementation of a `SyntaxNode` looks like. Specifically, it shows simplified code of the `Argument` class, which is used to represent an argument to a call. For example, the statement `F(42, foo: null);` contains two arguments: `42` and `foo: null`. An argument is composed of an expression, an optional name and an optional ref kind (`ref`, `out` or `in`). For brevity, the version of `Argument` shown here does not support arguments that have a ref kind. This means that the class has two properties: the lazy `Expression` and the non-lazy `Name`.

The implementation is composed of the following parts:

- Specification that the class directly inherits from the `SyntaxNode` base class and that it implements the `ISyntaxWrapper<TSyntax>` interface for Roslyn's `ArgumentSyntax` type.
- A field holding the most recent Roslyn syntax node, if any.
- An internal constructor that creates an instance of the class from a Roslyn syntax node.

  Notice that the lazy property `Expression` is not initialized here, while the non-lazy property `Name` is. Another interesting point is how complicated the expression used to initialize `Name` is, which shows that the CSharpE design is much simpler than the Roslyn design in this case.

  This constructor is used when a member of the `Arguments` collection of `InvocationExpression` or a similar kind of expression is accessed for the first time.
- A public constructor that can be used by the user to create a new instance of this class.
- The `Name` property.

  Because it is not lazy, it does not require any special behavior and so it can be an auto-property.

```
public sealed class Argument : SyntaxNode, ISyntaxWrapper<ArgumentSyntax>
{
    private ArgumentSyntax syntax;

    internal Argument(ArgumentSyntax syntax, SyntaxNode parent)
    {
        this.syntax = syntax ?? throw new ArgumentNullException(nameof(syntax));
        Name = syntax.NameColon?.Name.Identifier.ValueText;
        Parent = parent;
    }

    public Argument(Expression expression, string name = null)
    {
        Expression = expression;
        Name = name;
    }

    public string Name { get; set; }

    private Expression expression;
    public Expression Expression
    {
        get => expression ??
            (expression = FromRoslyn.Expression(syntax.Expression, this));
        set => SetNotNull(ref expression, value);
    }

    ArgumentSyntax ISyntaxWrapper<ArgumentSyntax>.GetWrapped(ref bool? changed)
    {
        GetAndResetChanged(ref changed);

        bool? thisChanged = false;
        var newExpression =
            expression?.GetWrapped(ref thisChanged) ?? syntax.Expression;

        if (syntax == null || thisChanged == true ||
            syntax.NameColon?.Name.Identifier.ValueText != Name)
        {
            syntax = RoslynSyntaxFactory.Argument(
                Name == null ? null : CSharpSyntaxFactory.NameColon(Name),
                default, newExpression);

            SetChanged(ref changed);
        }

        return syntax;
    }

    public static implicit operator Argument(Expression expression)
        => new Argument(expression);
}
```

Listing 16: Simplified implementation of the Argument class

- The `Expression` property.

  Since it is lazy, when its value is read for the first time, the `Expression` node is created based on the expression of the Roslyn node. The `FromRoslyn` class contains helper methods for converting Roslyn nodes to CSharpE nodes. In this case, it is used to create the correct type that derives from `Expression` based on the Roslyn node.

  The setter uses the helper method `SetNotNull`, which checks that the passed in value is not `null` and also ensures that the `Parent` property of the expression node is correctly set. (The `Parent` property is explained in more detail later.)

- The `GetWrapped` method.

  It is an explicit interface implementation, because C# does not allow implicit interface implementations through internal methods, only public ones, and this method should not be accessible by the user.

  The method does the following:

  1. Make sure that the value of the `changed` parameter is set correctly when this method is called by the parent node by invoking the helper methods `GetAndResetChanged` and `SetChanged` at the appropriate places.
  2. Call `GetWrapped` on its lazy properties if they are initialized, otherwise use the corresponding child of the saved Roslyn node. While doing this, keep track of whether any lazy properties reported changes in the `thisChanged` variable.
  3. Check if a new Roslyn node needs to be created. This happens either because no Roslyn node has been created yet, or because changes occurred since the saved Roslyn node was created. Changes are detected by checking the `thisChanged` variable for lazy properties and by comparing with the latest Roslyn node for non-lazy properties.
  4. Create a new Roslyn node by using a factory method from the Roslyn `SyntaxFactory` class (aliased as `RoslynSyntaxFactory` because of a conflict with CSharpE `SyntaxFactory`) and save it.
  5. Finally, return the Roslyn node, which is now guaranteed to be up to date.

  Note that the returned Roslyn node will have no parent. When the caller is the CSharpE parent node, it will incorporate that Roslyn node into its own Roslyn node, but with parent set to that node. This happens automatically when any Roslyn node with child nodes is created.

  To make this efficient, Roslyn uses a data structure called "red-green tree" (unrelated to the well-known red-black tree), where the regular nodes (which have parent references, and so cannot be reused) are a layer on top of hidden nodes with no parent references, which are reused. [22]

- An implicit conversion operator from `Expression` to `Argument`.

  This way, the common case where an argument has only an expression, without a name or a ref kind, can be created more easily.

Other syntax nodes generally follow this pattern, with some exceptions:

- Accessing any semantic information is more complicated.

  As explained in Section 1.2.3, Roslyn provides semantic information though the `Compilation` and `SemanticModel` classes. For example, to get the full name of a `NamedTypeReference`, such as the type reference `Task` in the field declaration `Task t;`, the following happens:

  1. The `Compilation` for the project is created.

     To do that, information from the whole project is necessary, which means that every node that exposes semantic information has to have access to the `Project` object. The way this is done is by making every node have a reference to its parent node. With that, the `SourceFile` that contains a node can be found by recursively walking parent references, and `SourceFile` contains a reference to its `Project`.
  2. The `SemanticModel` for the source file is created.
  3. A symbol corresponding to the node in question is retrieved from the `SemanticModel`.

     This requires using exactly the node that is part of the Roslyn syntax tree that was used to create the `Compilation`. As explained above, the node created by `GetWrapped` is not that: it has no parent node, and so it couldn't possibly be part of the syntax tree.

     To find the corresponding node that is part of the syntax tree, we use Roslyn Syntax Annotations. [23] The Roslyn node returned from `GetWrapped` is annotated with an annotation unique for the current CSharpE node. Then, a node with the same annotation is found in the syntax tree. Finally, that node is used to find the symbol through `SemanticModel`. This works, because incorporating Roslyn node into a parent preserves annotations.
  4. The symbol is used to find the desired information.

     In this case, that is the full name of the type of the field declaration, which could be (depending on references in the compilation and using directives in the file) for example `System.Threading.Tasks.Task`, `Microsoft.Build.Utilities.Task` or even a type with a name other than `Task` (if the file contains a using alias directive).

- Lists of syntax nodes have their own set of types.

  In the CSharpE API, lists of syntax nodes are represented as `IList<T>`. In Roslyn, such lists are either a `SyntaxList<T>` (for lists with no separator, such as members of a class) or a `SeparatedSyntaxList<T>` (for lists that use comma as a separator, such as arguments of a method call).

  To bridge this, CSharpE contains a set of internal list types, that also help with maintaining laziness. Such a list contains a collection, where each

```
public class ProjectTransformer
{
    public ProjectTransformer(
        IEnumerable<ITransformation> transformations, bool designTime);

    public event Action<LogAction> Log;

    public Project Transform(Project project);
}
```

Listing 17: API of the ProjectTransformer class

item can be either a Roslyn node or a CSharpE node. When an item in the list is accessed, it is converted to a CSharpE node, if it is not one already. When `GetWrapped` is called on the list, the result will include Roslyn nodes from the collection directly, while CSharpE nodes have to be converted by invoking their own `GetWrapped`.

- Exposed collections implement an interface for use in CSharpE.Transform smart loops.

  As explained in Section 3.2.2, CSharpE.Transform smart loops need to understand the collections they are iterating. For this reason, CSharpE.Syntax collections implement the `ISyntaxCollection<T>` interface. This interface implements the visitor pattern, so that a smart loop can correctly decide how to process the collection.

- Whitespace from user code is not preserved.

  When a syntax node is created using the Roslyn `SyntaxFactory`, it contains so called "elastic trivia", which is meant to be later replaced with proper trivia based on some formatting conventions. But if this step is not performed and the node is converted to a string, the result is invalid code. For example, `SyntaxFactory.ClassDeclaration("Foo").ToString()` returns `classFoo{}`, which is not valid C# code, because there is nothing separating the tokens `class` and `Foo`.

  The easiest way to fix this is to call `NormalizeWhitespace()`, though using that has the side-effect of reformatting all code, including code originally written by the user. But because the user is only ever going to see the reformatted code when debugging (as explained in Section 3.3), this was considered an acceptable solution.

4.2 CSharpE.Transform

Now that types necessary for representing and modifying code have been implemented, it is time to turn to code that will drive transformations. While Section 3.2 described the user-facing API of CSharpE.Transform, there is one more public type, `ProjectTransformer`, which is used by the Visual Studio and MSBuild extensions to run transformations. To isolate this type from user-facing types, it is placed in a separate namespace: `CSharpE.Transform.Execution`.

Listing 17 shows the API of `ProjectTransformer`. An instance of this class is created by specifying a collection of transformations and whether they should be executed in design-time or build-time mode. Next, we can subscribe to the `Log` event to diagnose how transformations are executed, as we have seen in Listing 13. (Note that this event does not follow the recommended pattern of using the `EventHandler<T>` delegate. [24] The approach used here is simpler and is sufficient for the purpose of subscribing to diagnostic information.) Finally, the `Transform` method is used to execute the transformations on the specified project.

The `Transform` method can be called repeatedly to keep executing the same transformations. If it is called for a project that contains code similar to previous project, results of transformations will be retrieved from caches, making the process more efficient.

Even though `Project` is mutable, the method does not modify its input and instead returns a new `Project` instance. This is done so that the caller can keep modifying the original project after the transformation is performed.

When a `ProjectTransformer` is created, it creates a `CodeTransformer` for each transformation. `CodeTransformer` handles efficiently executing that transformation. When the `Transform` method is called, a `TransformProject` is created for the input project, then each `CodeTransformer` is applied to it.

`TransformProject` is a type that inherits from `Project`, with some additions in support of executing transformations.

`CodeTransformer<TInput, TOutput>` is used to execute a piece of user code, which mutates its input and optionally also returns output. If the piece of code executed within a `CodeTransformer` has no output, unit type (i.e. type with no data and only one value) is used for the `TOutput` type parameter. But because .NET does not have a built-in unit type, and because this unit type does not have to be visible in the API of the library, a custom internal type called `Unit` is used.[1]

If the input of a `CodeTransformer` is a syntax node, it, or rather, its derived class, `SyntaxNodeCodeTransformer<TInput, TOutput>`, employs caching: When it is detected that the current input is equivalent to the previous input, changes from the previous input are directly applied to the current one, without recomputing them. Because there are variations to this process, it is represented as a delegate of the type `Func<T, Func<Action<T>>>`, which is somewhat similar to the curried form of a function type in functional programming. This delegate shape is used here, because the delegate is invoked in three stages, each at a different point in the process of executing the user code: the first stage is invoked before the code is executed (and is provided with the input syntax node), the second stage is invoked after the code is executed (and does not have input of its own, because all it needs is the syntax node, which was already provided in the previous stage and has been mutated since then), and the third stage can be repeatedly invoked whenever there is a next equivalent input (and is provided with that input).

[1] The `ValueTuple` family of types, which were added to .NET to support C# tuples, includes the non-generic `ValueTuple` type, representing a tuple with zero elements, even though there is currently no support for zero-element tuples in C#. This type could be used as a unit type, but a custom type with the name `Unit` makes the intention clearer.

Specifically, the variations of this delegate are:

- Regular.

  For most user code, the "before" stage does nothing, syntax is retrieved from the input during the "after" stage (by calling `GetWrapped` on it) and the input of the "next" stage is mutated by forcing this syntax into it.

- Smart segment.

  User code that executes within a smart segment requires special handling. The only valid changes within such segment are adding new members. This means that if the delegate only preserves these new members, the concept of equivalence can be broadened, resulting in more cache hits.

  To do this, the number of members of the input is recorded in the "before" stage, then members above this count are saved in the "after" stage, and finally, these members are added to the input of the "next" stage.

- Using directives.

  The code that executes within a `SyntaxNodeCodeTransformer` is not allowed to modify syntax outside of its input, with one exception: `using` directives. When newly added syntax nodes reference a type from a namespace that does not have a `using` directive in the file yet, CSharpE adds the directive automatically. But this has to be replicated also when those syntax nodes are being added from a cache. For this purpose, `SourceFile` includes functionality to record requests to ensure a `using` directive exists.

  In the "before" stage, this recording is started on the input, in the "after" stage, recording is stopped and its results retrieved and for the input of the "next" stage, the recorded namespaces are requested again. This happens on top of one of the two delegates described above.

This caching is at the core of ensuring that user code is not executed unnecessarily in CSharpE.Transform and it is what each "cached" line in Listing 13 represents. But to make this work, each `CodeTransformer` also has to maintain information about the execution of smart loops and segments within it.

This information is kept in a list of objects of type `CollectionTransformer`. When a smart loop or segment is invoked within user code, information about it is matched against an object from the list. If the match is successful, the old object is reused, otherwise, new `CollectionTransformer` is created.

Since the user code in question is always the same, it is expected that it will usually invoke the same smart loops and segments when it is executed, which should result in high levels of reuse of `CollectionTransformer` objects.

Specifically, each object in the list is a `CollectionTransformer<TParent, TItem, TData, TIntermediate, TResult>`. The meaning of the type parameters for a smart loop is:

- `TParent` is the type that contains the collection.
- `TItem` is the type of items in the collection.

- `TData` is the type of data that is used as input for user code.
- `TIntermediate` is the result type of each iteration of the smart loop.
- `TResult` is the result type of the whole smart loop.

A smart segment behaves in many respects like a smart loop over a collection with a single element. This means that for example both `TParent` and `TItem` are `TypeDefinition` for them. Another case where some of the type parameters are effectively unused is for smart loops that do no return a value: in that case, both `TIntermediate` and `TResult` are `Unit`.

To further clarify the meaning of the type parameters, consider the following example code, modified from Listing 14:

```
1 var fieldsList = Smart.ForEach(classDefinition.Fields, classDefinition.Name,
2     (className, field) => (className, field.Type, field.Name));
```

The `CollectionTransformer` used for this code has the following type parameters:

Type parameter	Value
`TParent`	`SyntaxNode` (for `classDefinition`)
`TItem`	`FieldDefinition`
`TData`	`string` (for `classDefinition.Name`)
`TIntermediate`	`(string, TypeReference, string)`
`TResult`	`List<(string, TypeReference, string)>`

What the implementation of `CollectionTransformer` actually does is that it maintains `CodeTransformer` objects and whenever it processes a collection, it reuses one of these objects, if it matches the item that is currently being processed. There are two variants of `CollectionTransformer` and each of them does this differently:

- `SourceFileCollectionTransformer` is used when processing source files in a project. Files are considered to match when they have the same path (including file name).
- `SyntaxNodeCollectionTransformer` is used when processing syntax nodes within a file. Syntax nodes are considered to match based on a diff of the parent node. This way, when some nodes are added to or removed from the collection, the remaining nodes (including those that were changed) should still have their `CodeTransformer` reused.

In both cases, when `CodeTransformer` objects are reused, it means that their matching comes into effect, which can lead to avoiding rerunning the relevant piece of user code, thanks to caching.

4.3 CSharpE.Transform.MSBuild

Now that CSharpE.Transform has been implemented, it is time to use it. First, we create an MSBuild `Task` to support executing build-time transformations from IDEs or from the command line. MSBuild has variants for both .NET Framework and .NET Core and both will need to be capable of running this `Task`, because the .NET Framework variant is used by Visual Studio and the .NET Core variant is required by Linux build servers. This means that the `Task` will have to be capable of running on both frameworks.

The `Task` will need to load referenced extension assemblies to execute the transformations contained within them. To avoid issues with assembly loading we could take advantage of assembly isolation (`AppDomain` in .NET Framework and `AssemblyLoadContext` in .NET Core) either directly or by using a library, [25] but this approach does not seem to be reliable. So, a separate process is used instead.

The way it works is that the assembly with the `Task` is loaded as a regular MSBuild extension library. It then relaunches itself as an application, which actually executes the transformations. The two processes communicate with each other using a rudimentary text-based protocol: the MSBuild extension writes paths of references (including references to CSharpE extensions) and input source files to the standard input of the second process and then reads warnings, errors and paths of transformed source files from its standard output.

The MSBuild process is generally not reused between builds, which means this approach will always execute full transformations, with no caching. This is acceptable, because building is not particularly performance sensitive, certainly significantly less sensitive than IDE operations like autocompletion.

MSBuild `Task`s are usually executed not just during regular build, but also during "design-time build". [26] Because such builds are used by IDEs, but CSharpE requires special handling for those, the `Task` described in this section specifically does not execute during design-time builds.

4.4 CSharpE.Transform.VisualStudio

After support for MSBuild, the next step is to add support for the Visual Studio IDE. Most of the support in Visual Studio for C# comes from a Visual Studio extension that is open source and part of the Roslyn project, but this support is not useful for CSharpE on its own, because it has no knowledge of CSharpE transformations. Possible approaches to make this work are:

1. Attempt to extend the C# extension, so that it also supports CSharpE.
2. Improve the C# extension to make it more suitable for extending to support CSharpE.
3. Modify the C# extension to support CSharpE, by creating a fork of Roslyn.
4. Implement support for CSharpE from scratch, without using the existing support for C#.

Option 1 looks promising at first: Visual Studio and the C# extension use Managed Extensibility Framework (MEF) for their components, which means it could be possible to replace the C# components with CSharpE components.

Specifically, this can be accomplished thanks to the way the C# extension uses MEF. When the relevant components are resolved, only the one with the highest `ServiceLayer` is selected. This means that CSharpE components will be chosen, if they specify higher `ServiceLayer` than the corresponding C# components.

Another question is: which components to replace? For example, the Roslyn API contains the abstract class `CompletionService`. Creating a class that derives from it allows specifying which items show in code completion. But there is no such component that would allow overriding which errors and warnings show in the Error List, which is necessary to make CSharpE work well in Visual Studio.

Roslyn also contains more low-level services: `ISyntaxTreeFactoryService` and `ICompilationFactoryService`, that allow using custom `SyntaxTree` and `Compilation` objects. Overriding those should be enough; unfortunately, they are internal.

Though all is not lost: .NET includes support for the undocumented attribute `IgnoresAccessChecksToAttribute`. [27] Applying this attribute is enough for run-time, but because the C# compiler does not understand the attribute, more work is necessary at compile-time. That work can be done by an MSBuild task, which rewrites referenced assemblies by changing internal members to public ones.[2][28]

The big issue with this approach is that it leads to code that is likely going to be extremely brittle: Whenever the C# extension is updated (which usually happens with every minor version of Visual Studio), there is a high chance that it will break the CSharpE extension, because it relies on internal implementation details, which are subject to change.

Option 2 is an attempt to make Option 1 less brittle: if the public extensibility points offered by the C# extension were expanded to support the needs of CSharpE, the chance that an update to the C# extension would break the CSharpE extension would be significantly diminished. The issue with this option is that it requires cooperation from the maintainers of the C# extension, which is uncertain.

Option 3 would be to create a version of the C# extension with support for CSharpE, instead of building the CSharpE extension on top of the C# extension. Doing this would require creating and maintaining a fork of the Roslyn repository. The advantage, compared with Option 1, is that there would be no need to use problematic techniques like `IgnoresAccessChecksToAttribute`. The disadvantage is that this could make the CSharpE extension even more brittle with respect to changes in Roslyn: a change in Roslyn that would not affect Option 1 could still cause a merge conflict with this approach.

Option 4 is to create an extension for CSharpE that is largely independent of the C# extension, though it could reuse some of its services. This approach avoids

[2]At first sight, this might look like a good opportunity to use CSharpE. But CSharpE is designed for rewriting source code written by the user, not rewriting referenced assemblies. Doing that requires manipulating metadata, not source code, which is why CSharpE is not useful for this purpose. The referenced project uses Mono.Cecil for its metadata manipulation.

the brittleness issues of Options 1 and 3 and the dependency on maintainers of Roslyn of Option 2. But it would likely require a significant amount of work to reimplement all the necessary services and the end result would probably still not be on a par with what is offered by the C# extension.

For the long-term health of the CSharpE project, Option 2 would be ideal. If that proved infeasible, then Option 4 might become necessary. But because this is currently only a short-term project, Option 1 was chosen instead.

What this means is that the Visual Studio extension for CSharpE implements `ISyntaxTreeFactoryService` and `ICompilationFactoryService` in such a way that they override their C# versions. These services are used to provide custom implementations of `SyntaxTree`, `Compilation` and `SemanticModel`. All of these generally delegate to their C# versions, except that syntax nodes and file locations often have to be mapped back and forth between the original source code and source code after all design-time transformations have been run.

For mapping between nodes, Roslyn Syntax Annotations are used: nodes in original trees are annotated before transformations are run. Then, if semantic information about a node is requested, a node with the same annotation in the corresponding transformed tree is located and its information is returned instead. Since a transformation can remove or replace nodes, this process can fail, with no information being returned.

For mapping between source file locations, annotations are not fine-grained enough, so diffs are used instead. Roslyn contains the `SyntaxDiffer` class for computing diffs between syntax trees, but this was insufficient. Because of that, an enhanced copy of this class is used.

The core of the CSharpE Visual Studio extension is in its implementation of `Compilation`: it contains the original C# `Compilation` and also a lazily computed C# `Compilation` containing code with design-time transformations applied. These two `Compilation`s are then used as appropriate to implement the required `abstract` methods. `ProjectTransformer`, described in Section 4.2, is used to compute the compilation with transformations applied. Because the `Compilation` class is immutable and considered thread-safe, a single instance of `ProjectTransfomer` is used under a mutex for successive modified instances of `Compilation`, so that transformations of code that hasn't changed do not have to be recomputed. One exception is when these modifications include changes to references: a new instance of `ProjectTransformer` is used in that situation, in case a modified reference included a transformation, because `ProjectTransformer` operates on a fixed set of transformations.

When a project that uses CSharpE is executed within the Visual Studio Debugger, the code that is displayed to the user is the one produced by MSBuild, which means it is the user code, after performing build-time transformations. So, the code shown to the user is the code that is actually executing, which is especially useful when developing a transformation or when debugging an issue related to the used transformations.

At the same time, a transformation can introduce a large amount of "boilerplate code" (which is one of the main reasons why transformations are useful in the first place), and this additional code can hamper understanding how the user code executes. While this means that some kind of simplified debugging view

could be useful, it has not been implemented.

Figures 4.1, 4.2, 4.3 and 4.4 show how a very simple CSharpE extension for creating immutable records works in Visual Studio. What the extension does is that it takes a class marked with an attribute and containing some fields and turns it into a proper immutable record with a constructor, read-only properties and `With` methods for creating modified instances. The figures show that Visual Studio features work using CSharpE semantics, not C# semantics. For example, notice that invoking the parameterless constructor produces an error, while invoking the constructor with parameters corresponding to fields does not. This is the opposite of what would happen in regular C#.

TODO: Conclusion?

4.5 Example extensions

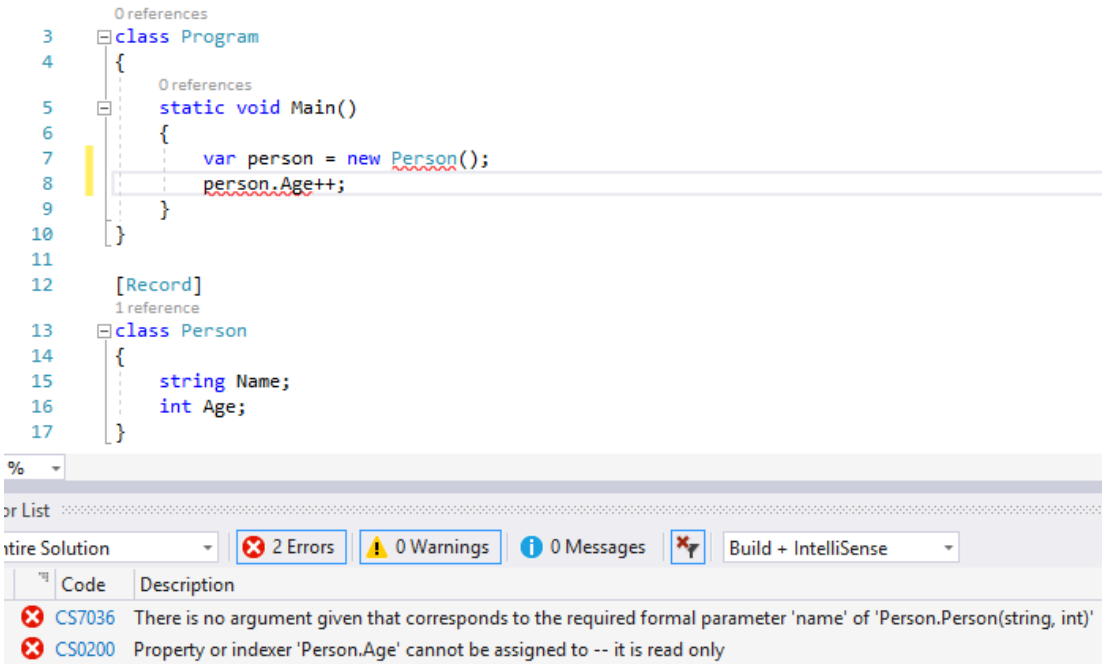


Figure 4.1: Example of error reporting

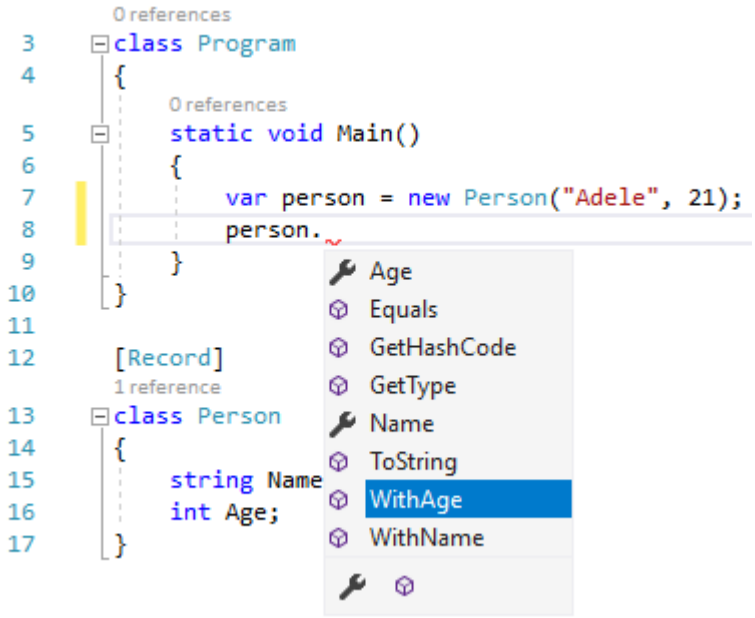


Figure 4.2: Example of autocompletion

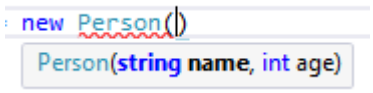


Figure 4.3: Example of parameter info

Figure 4.4: Example of QuickInfo

5. Comparison with existing tools

5.1 Reading and writing code

5.2 Transforming code

6. Future work

- Optional build-time only IL transformation step (brings advantages of IL transformations, while limiting its disadvantages)

Conclusion

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List of Figures

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List of Abbreviations

AOP	aspect-oriented programming
AoS	array of structures
API	Application programming interface
CI	Continuous integration
CLI	Common Language Infrastructure
CodeDOM	Code Document Object Model
DLR	Dynamic Language Runtime
IDE	integrated development environment
IL	Intermediate Language
JIT	just-in-time
LINQ	Language Integrated Query
MEF	Managed Extensibility Framework
SoA	structure of arrays
SQL	Structured Query Language
T4	Text Template Transformation Toolkit
VB.NET	Visual Basic .NET
XML	Extensible Markup Language
XSLT	Extensible Stylesheet Language Transformations

A. Attachments

A.1 First Attachment