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Last but not least, I thank Google for supporting students to work on interesting open source projects.

Typography

Vertical line denotes citations. …

Terminology

Debugger – a program which controls execution and observes the state of another program.

Debuggee – the process being debugged by the debugger.

IDE – Integrated development environment. A collection of software developments tools such as a code editor, a debugger etc.

By the term collection this thesis refers to .NET Lists, ObservableCollections, arrays, or any other IEnumerables. Similar classes exist in other environments and most ideas mentioned in this thesis would apply also to them.

Permanent reference – a Debugger.Value which has been made permanent and does not become invalid when the debuggee is resumed. – mention this terminology here or only later in the Debugger section? It is used throughout the thesis, after it was defined in the Debugger section of course.

Context

This thesis is about debugging managed programs in the context of .NET environment. Therefore, whenever the text mentions classes and their instances, it refers to managed .NET instances, references etc. Likewise, the term **object** **properties** in the context of this thesis refers to standard .NET properties – i.e. a getter and/or a setter method usually with a backing field. Still, a lot of concepts and ideas described in this thesis can be directly applied to other managed environments, for example Java.

# Introduction

The idea for this thesis comes from a desire for better debugging features in current IDEs. I had a vision about innovative ways of debugging – namely debugging object graphs and collections, and I implemented this vision as new functionality for SharpDevelop – the open source IDE for .NET. This thesis first describes the motivation behind this functionality – that is why to build new features even though developers could live without them so far. Then, detailed analysis of the solutions is presented, including an overview of SharpDevelop architecture and means of integration of the work into SharpDevelop. Finally, this thesis describes the design of the codebase and highlights interesting parts of the implementation.

## Preview – remove

To give the reader a picture of our work right in the beginning, Let’s start with a preview of the features implemented.

### Object graph visualizer

Our first addition to SharpDevelop debugger is a visualizer of object graphs.

Screenshot

While debugging, the Object graph visualizer lets users explore object graphs referenced by the variables in user code. For example, if there is an instance of a linked list in the program, the visualizer displays the linked list in a similar fashion it is commonly drawn on a whiteboard. The graph is updated live as the user steps in the debugger and the state of the data structure changes.

### Collection visualizer

The second addition to SharpDevelop debugger is a collection visualizer – a useful way to explore contents of collections of objects.

Screenshot

While debugging, the Collection visualizer provides insight into the contents of collections of objects. The main point is that it displays properties of the collection items in a way which makes multiple properties of each item visible at once.

### Debugger tooltips

The third feature which was added to SharpDevelop are debugger tooltips.

Screenshot IEnumerable

Debugger tooltips are a popular feature of Visual Studio. SharpDevelop 3 has debugger tooltips but two important features were missing - support for IEnumerable collections, and support for large collections. As a part of this thesis the tooltips were reimplemented in WPF for SharpDevelop 4.0, including added support for IEnumerable collections and large collections.

## Contribution of this thesis

The visualizers described in this thesis come completely from the ideas of the author of this thesis. As a result of this thesis SharpDevelop is currently the only IDE to have such features and we are expecting user feedback to see how these features help users in their every-day development tasks. Some users have already provided positive feedback – for example, they expressed a need for a better Collection debugging support in other IDEs.

## Background

The first ideas for this thesis come from the beginning of 2009 when I was experimenting with visualizing object graphs using the Visual Studio debugger (<http://coding-time.blogspot.com/2009/03/debugger-visualizer-for-visual-studio.html>, thinking about improving the way people debug data structures. Then I found about Google summer of code 2009 from a poster at the Faculty of Mathematics and Physics in Prague. Seeing that SharpDevelop IDE was among the mentoring organizations and the team wanted to improve their debugger, applying to SharpDevelop in Google summer of code was a clear choice.

Google summer of code (http://code.google.com/soc/) is a program run by Google. Open source organizations apply to the program and Google selects the most attractive organizations to participate. Among participating organizations are such ones as Eclipse, Firefox, gcc, Haskell, Mono, Ogre3D, OpenOffice, Scala and many others. The students then apply to individual organizations with detailed proposals of their ideas. Google distributes approximately 1000 slots to the organizations, based on how popular the organization is (that is how many applications the organization received). For example, SharpDevelop had five slots in 2009. Then it is up to the mentoring organization members (that is, the long-term contributors to the open source project) to select the students they like the most. These students then work for 3 months fulltime on their projects and receive $5000 from Google, provided the mentoring organization confirms that the student did a good job. The not-so-unofficial goal of Summer of code is that students stay with the project after the summer and become contributors.

My experience with working on SharpDevelop has been very positive mainly because the SharpDevelop team is made by the best programmers I have had an opportunity to work with. They deserve a lot of respect not only for contributing their skills and free time, but also for the quality of their work. SharpDevelop is a very good source for learning about design, coding practices and technologies. Moreover, the team members are helpful and discussions with them are effective.



Image - SharpDevelop meeting in August 2009 in Bad Ischl, Austria. Left to right: Tomasz Tretkowski (Gsoc: C++ Backend Binding), Daniel Grunwald (Senior Developer, Architect), Martin Koníček (Gsoc: Debugger visualizers), Siegfried Pammer (Gsoc: Xaml Binding), David Srbecký (Debugger), Peter Forstmeier (SharpDevelop Reports), Christoph Wille (Project Management).

# Motivation and goals

Sjednotit a rozhodnout se az v analyze, ze to budou 3 features?

The introduction section provided short previews of the features covered in this thesis. This section described the motivation for this thesis. – jestli nebude preview tak vyhodit

Debuggers and Integrated Development Environments are a very live topic in software engineering and they have seen a lot of improvement over the last years. However, current debuggers still do not solve some scenarios sufficiently and this section identifies such scenarios.

## Object graphs

Currently, most visual debuggers are similar in terms of presenting data from the debuggee to users. The most typical way of presenting such data are **watches**, which show variables in current scope in a tree view fashion - if an object contains references to other objects, these become its children in the tree. **Debugger tooltips** are a very similar feature to watches but they show the expression at the mouse cursor hovered over the code being debugged. This makes debugger tooltips more comfortable to use than watches, since users do not have to look for the right variables in the watch window and switch their concentration between the watch window and code editor. – subjective?

(screenshot Eclipse watch, tooltips)

But neither debugger tooltips nor watches are perfect for all scenarios – take, for instance, a structure of two objects having a reference to each other:



The picture shows how people naturally depict such structures. However, this is how such structure is presented by watches or debugger tooltips:



As we can see, the expansion can continue infinitely and users have very little means of determining how the structure actually looks in reality.

Another thing which is not very well solved today is visualizing *changes*. If a user makes a step in the debugger how can he or she determine the changes to the state of the program? Sometimes the change is easy to understand from the code, as in:

IFoo foo = GetFooImplementation(context);

But if the code being stepped over changes multiple variables, it is useful for the user to see what just happened. This is solved in some IDEs by highlighting the variables whose values were changed.

Red variables in VS watches – screenshot

On this screenshot from Visual Studio we can see the variables whose values were changed since the last time the debuggee was stopped (for example, before a step).

Unfortunately, this approach is not great for visualizing changes in data structures. What if an item was inserted into a linked list? Or what if a tree rotation occurred? I had realized this problem when teaching Introduction to programming to university freshmen. What I frequently observed was that there had been code on one side of the whiteboard and a drawing of a data structure on the other side. I was explaining the code by pointing to the current “instruction pointer” with a finger and moving the finger from one line of the program to the next line. At the same time a student was updating the drawing of a data structure by erasing parts of it and drawing new parts, as the structure was being modified. By seeing how each statement modified the data structure the students could clearly see how the program works.

After several weeks of running this university class I had an idea – why not automate the process? The IDE could actually let users step through the code and draw and update data structures in a similar way we did on the whiteboard in the class.

### Goals

This thesis sets two main goals to address the described issues:

* Provide a way for users to see the state of data structures in the program in a similar way people draw data structures on a whiteboard.
* Make it possible for users to see how data structures are being changed by stepping in the debugger. The more understandable the visualization of the change, the better.

## Collections

The second issue with current IDEs are insufficient possibilities to explore and understand contents of collections of complex objects. For example, when debugging a program that works with a collection of objects of type Person, such collection is commonly visualized in the following way in current debuggers:

Screenshot tooltip with 1 item expanded

The problem is that there is no quick way to get an overview of the contents of the collection and there is also no way to quickly locate an individual item. The only possibility is to drill down the items of the collection, opening and closing them one by one, which takes a lot of time. Combined with the fact that collections are being debugged very often, this is a serious shortcoming of current debuggers.

Specifically to SharpDevelop, its integrated debugger currently lacks support for IEnumerable collections and does not support large collections in an acceptable way (debugging large collections can block whole SharpDevelop for large amounts of time, depending on the size of the collection).

### Goals

This thesis sets the following goals to address the described issues:

* Provide a way for users to get an overview of contents of collections of objects, in an easier, faster way than with watches and debugger tooltips.
* Add support for IEnumerable collections to SharpDevelop’s integrated debugger.
* Add efficient support for large collections (tens of thousands of items) to SharpDevelop’s integrated debugger.

## Debugger tooltips

Debugger tooltips are a feature similar to watches, as shown on the following screenshot from Visual Studio:

Screenshots tooltips VS2010.

The advantage of debugger tooltips compared to watches is that users can just hover the mouse over anything they are interested in. They don’t have to search the watch window which contains typically more than a dozen of available variables. Debugger tooltips are a frequently used feature of Visual Studio’s integrated debugger and SharpDevelop implements them as well. However, the debugger tooltips in SharpDevelop 3 are missing two very important features: support for large collections, and support for the IEnumerable type. The importance of support for IEnumerable is very high since typical programs use IEnumerable extensively. Moreover, the UI of SharpDevelop 3 was built using Windows Forms and starting with SharpDevelop version 4.0, Windows Forms has been deprecated in and the UI has been rewritten to WPF. That means that completely new tooltips implemented in WPF are needed, and this thesis covers a new implementation of debugger tooltips for SharpDevelop’s integrated debugger.

### Goals

To address the absence of needed features in the debugger tooltips and the switch to new UI framework, this thesis sets the following goals:

* Support all IEnumerable collections.
* Support large collections without noticeable degradation in performance.
* Implement the UI using WPF.
* Make it possible to open the Object graph visualizer and Collection visualizer from the tooltips.

# Analysis

Having motivation and high-level goals for the thesis laid out, this section provides detailed analysis of the means, options and solutions.

## Introduction to SharpDevelop IDE

SharpDevelop (<http://www.icsharpcode.net/opensource/sd/>) is a free open source IDE for .NET written almost entirely in C#. Its development started from scratch in 2000. Version 4.0 (as of April 2011) supports development in C# 4, Visual Basic 10, F#, IronPython, Boo and C++.

screenshot

The level of support for the individual languages varies. For example, F# code-completion is currently under development. Support for C# in SharpDevelop is well comparable to Visual Studio and in some areas, SharpDevelop surpasses Visual Studio. Regarding C++ support, Visual Studio definitely surpasses SharpDevelop, but C++ is not the main focus of SharpDevelop. All this information is for SharpDevelop 4.0 as of April 2011.

SharpDevelop runs on Windows (for Linux there is MonoDevelop which was forked from an early version of SharpDevelop). SharpDevelop uses .NET SDK for the build process (that is MSBuild and the compilers for individual languages). SharpDevelop 4.0 supports targeting .NET versions 2.0, 3.0, 3.5 and 4.0. SharpDevelop uses the project and solution file format of Visual Studio – therefore, it can be used side-by-side with Visual Studio without problems.

SharpDevelop (as of April 2011) does not fully support the following functionality:

* Web application development. It is possible to build and debug an ASP.NET application using SharpDevelop (http://community.sharpdevelop.net/blogs/marcueusebiu/archive/2010/12/28/sharpdevelop-classic-asp-net-websites-using-iis-express.aspx). However, the tooling (.aspx code completion etc.) is currently not implemented.
* WPF designer is work in progress.

As SharpDevelop is completely free, it makes sense to compare it to the Express version of Visual Studio. SharpDevelop has the following features which are not present in Visual Studio Express:

* Integrated profiler
* NUnit integration (with test runner in SharpDevelop)
* Subversion and Git integration out of the box
* Code coverage
* ILSpy integration (open source .NET decompiler, developed by the SharpDevelop team)
* Reports (developed as part of SharpDevelop)
* Debugger visualizers
* Productivity features (ReSharper-like)
* Extensibility

Of course, there are many small differences on both sides, but this should give a basic overview.

The last mentioned feature, Extensibility, is important: SharpDevelop can be extended or modified in almost any way. Its API is well designed and in case there would be an extension point missing, the team is open to good contributions. Being an open source IDE written entirely in C# makes SharpDevelop a very interesting project for programmers interested in .NET who would like to learn advanced topics and have their work used by many people (SharpDevelop is currently being downloaded around two thousand times a day).

## The architecture of SharpDevelop

This section provides a high-level look at the architecture of SharpDevelop, its extensibility model and how the Debugger visualizers fit into the picture.

### Reusable parts of SharpDevelop

Several parts of SharpDevelop are written as standalone libraries. These include:

* ICSharpCode.Core – the generic extensibility framework on which SharpDevelop is built
* NRefactory (C# and VB parser and AST)
* ICSharpCode.SharpDevelop.Dom (representation of type system)
* AvalonEdit (code editor with syntax highlighting and code completion window)
* Debugger
* Profiler
* Usage data collection (collecting data about how users interact with the application and uploading them to a server)
* Reports (reporting library)

All of these libraries are completely reusable. Most of them are integrated into SharpDevelop by AddIns which act as a “glue” to provide the functionality of the libraries in SharpDevelop. E.g. Debugger.Core is a managed debugger library and Debugger.AddIn contains user interface and SharpDevelop-specific logic. In the same fashion, AvalonEdit is a code editor with support for syntax highlighting and AvalonEdit.AddIn adds SharpDevelop-specific behavior, like split-view, context actions etc.

### ICSharpCode.Core

SharpDevelop is an application built using a generic extensibility framework called ICSharpCode.Core (further referred to as the Core). The Core provides an AddIn infrastructure, where AddIns can extend almost anything, including other AddIns. The main point of the Core is to allow users to provide extension points in their applications very easily.

The Core was developed for the purposes of SharpDevelop but it is a standalone framework on which SharpDevelop is built.

#### ICSharpCode.Core for WPF and Windows Forms applications

There are two versions of the Core: ICSharpCode.Core.WinForms and ICSharpCode.Core.Presentation, designed to be used in Windows Forms and WPF applications respectively. They both reference the assembly ICSharpCode.Core which contains all the common non-UI-specific functionality.

#### The AddIn tree

The extensibility infrastructure provided by the Core is called the AddIn tree. AddIns are defined in XML files with .addin extension. There are several standard tags, the basic one being a tag called Path which essentially enables adding extension points. Here is an example , where four ToolBarItems are being added to the AddIn tree to a path called “SharpDevelop/Browser/Toolbar”:

<Path name = "/Browser/Toolbar">

<ToolbarItem id = "Back"

icon = "Icons.16x16.BrowserBefore"

tooltip = "${res:AddIns.HtmlHelp2.Back}"

class = " SharpDevelop.BrowserDisplayBinding.GoBack"/>

<ToolbarItem id = "Forward"

icon = "Icons.16x16.BrowserAfter"

tooltip = "${res:AddIns.HtmlHelp2.Forward}"

class = " SharpDevelop.BrowserDisplayBinding.GoForward"/>

<ToolbarItem id = "Separator1" type = "Separator"/>

<ToolbarItem id = "GoHome"

icon = "Icons.16x16.BrowserHome"

tooltip = "${res:AddIns.HtmlHelp2.Homepage}"

class = "SharpDevelop.BrowserDisplayBinding.GoHome"/>

[...]

Then the application built using the Core can call the following API:

toolStrip = ToolbarService.CreateToolStrip(this,

"/Browser/Toolbar");

this.Controls.Add(toolStrip);

Which returns a ToolStrip object, with 3 buttons and a separator, as defined in the .addin xml file.

This functionality by itself wouldn’t be very interesting. The interesting part comes when someone else writes an addin for the application, specifying the following in the addin definition file:

Code listing title - HelpAddin.addin

<Path name = "/Browser/Toolbar">

<Condition name="IsFileOpen" action="Disable">

<ToolbarItem id = "SyncHelpTopic"

icon = "Icons.16x16.ArrowLeftRight"

tooltip = "${res:AddIns.HtmlHelp2.SyncTOC}"

class = "HtmlHelp2.SyncTocCommand"

insertafter = "Separator1"/>

[...]

Now, the call to ToolbarService.CreateToolStrip will now return a ToolStrip with four buttons. That happens because the AddIn tree combines all the addin definitions together. By creating the toolbar using the Core API, the host application has made its toolbar extensible. The more the host applications uses such calls, the more extensible it will be.

The second code listing also shows a standard construct called Condition. The Condition causes the ToolbarItem to be enabled only if the SolutionOpen condition evaluates to true. The Condition has custom logic implemented in a C# class, which has to be registered in the following way:

<Runtime>  
        <Import assembly=":HelpAddin">  
            <ConditionEvaluator name="IsFileOpen" class="HelpAddin.IsFileOpenConditionEvaluator"/>

…

In the listings one can also notice that each of ToolbarItem xml tags has a number of attributes. The attribute **class** determines the name of the class the toolbar button click. The **insertafter** attribute specifies at which position the item should be inserted. Insertafter refers to an **id** of another item. The final order of items is resolved from the insertafter relations by a topological sort algorithm. If the sort fails then an arbitrary order is used.

So far the examples have shown two types of tags which can be inserted inside a Path in the AddInTree: Condition and ToolbarItem. These xml tags are called **codons** in SharpDevelop terminology. There are six types of default codons(make it a table):

* Class - Creates object instances by invocating a type's parameterless constructor.
* FileFilter - Creates file filter entries for the OpenFileDialog or SaveFileDialog.
* Include - Includes one or multiple items from another location in the addin tree. You can use the attribute "item" (to include a single item) **or** the attribute "path" (to include all items from the target path).
* Icon - Used to create associations between file types and icons.
* MenuItem - Creates a System.Windows.Forms.ToolStrip\* item for use in a menu.
* ToolbarItem - Creates a System.Windows.Forms.ToolStrip\* item for use in a toolbar.

The **class** codon is very useful when providing extensibility not related to user interface. A typical usage is to register classes implementing an interface provided by the host application at a well-known Path:

Listing title ICSharpCode.Debugger.Addin.addin.

<Path name="/SharpDevelop/Services/Debugger/Visualizers">  
        <Class class="Debugger.AddIn.Visualizers.ObjectGraphVisualizer" />  
 </Path>

Then the host application can obtain all the available implementations:

Listing title Code in SharpDevelop

AddInTree.BuildItems<IVisualizer>("/SharpDevelop/Services/Debugger/Visualizers")

Such call assumes that all the classes registered at the Path /SharpDevelop/Services/Debugger/Visualizers implement IVisualizer interface.

Further in Implementation mention how we are using Class to register debugger visualizer.

##### Lazy loading

To improve application startup time, the parts of the AddIn tree are only loaded when needed. For example if an AddIn only adds items to a menu, the AddIn assembly will not be loaded until the menu is first opened.

##### Doozers and more extensibility – maybe remove

So far, we have seen six default types of codons (Class, FileFilter, Icon, MenuItem, Toolbar). All the codons are actually not hardwired into the AddIn tree implementation. There is a general mechanism of turning codons (i.e. the xml tags) into objects. And even this mechanism is extensible as well. Each of the codons has a corresponding builder which can build an object out of the codon. These builders are called **doozers** – e.g. ClassDoozer for Class codon, MenuItemDoozer for MenuItem codon etc. The extensibility means that we can implement our own doozers for our own new codons, to define e.g. a new xml tag (codon) called *Debugger*:

<Path name="/SharpDevelop/Services/DebuggerService/Debugger">  
        <Debugger id="DefaultDebugger"  
                  supportsStepping = "true"  
                  supportsExecutionControl = "true"  
                  supportsAttaching = "true"  
                  supportsDetaching = "true"  
                  class="ICSharpCode.SharpDevelop.Services.WindowsDebugger"/>

</Path>

This is a good way to pass parameters from the .addin xml file to the object that will be constructed. As we said, we defined a new *Debugger* codon by defining a new Doozer. The last thing we have to do is to register this doozer in the Runtime section of the AddIn tree.

<Runtime>  
        <Import assembly=":ICSharpCode.SharpDevelop">  
 <Doozer name="Debugger" class="ICSharpCode.SharpDevelop.Debugging.DebuggerDoozer"/>  
 [...]  
 </Import>  
</Runtime>

Now the Core knows that when it encounters an xml tag called *Debugger*, it processes it using our *DebuggerDoozer* class.

Maybe show IDoozer definition.

Another codon we saw in one of the listings was a Condition:

<Condition name = "SolutionOpen" action = "Disable">

The SolutionOpen condition is provided by a class called SolutionOpenConditionEvaluator. Like Doozers, the condition evaluators have to be registered in the Runtime section of the AddIn tree in the following way:

<Runtime>  
        <Import assembly=":ICSharpCode.SharpDevelop">  
<ConditionEvaluator name="SolutionOpen" class="ICSharpCode.SharpDevelop.SolutionOpenConditionEvaluator"/>  
 [...]  
 </Import>  
</Runtime>

Maybe show IConditionEvaluator definition.

#### Localization

In XML: label = "${res: AddIns.Profiler.ProfilingView.CpuCyclesText }"

In code: StringParser.**Parse**("${res:AddIns.Profiler.ProfilingView.CpuCyclesText}")

The resource identifier can be any string but in SharpDevelop we are using namespace-like notation to prevent collisions.

#### PropertyService

maybe

#### Remarks

For more information about SharpDevelop.Core see <http://www.codeproject.com/KB/cs/ICSharpCodeCore.aspx> and http://www.codeproject.com/KB/cs/LineCounterSDAddIn.aspx

### ICSharpCode.SharpDevelop

As said before, SharpDevelop is an application built using ICSharpCode.Core. The codebase of SharpDevelop itself consists of many AddIns. Even the IDE “itself” is an AddIn – contained in the project ICSharpCode.SharpDevelop, with the AddIn definition file ICSharpCode.SharpDevelop.addin. The SharpDevelop AddIn contains the base of SharpDevelop UI and a part of functionality but it is not a working IDE - it rather provides interfaces to be implemented by AddIns. For example, code editing, code completion, and debugger are all implemented as AddIns extending ICSharpCode.SharpDevelop.

### NRefactory

NRefactory is the object model for C# and VB code. The debugger is using NRefactory Expressions to represent expressions to be evaluated and the Debugger visualizers use NRefactory Expressions extensively.

#### AST

INode <- AbstractNode <- different types, most important Statement and Expression. Almost all of them generated – how?

#### Visitors

Classical visitor pattern: INode.AcceptVisitor. e.g. ForStatement.AcceptVisitor just calls visitor.**VisitForStatement.**

IAstVisitor <- AbstractAstVisitor, NodeTrackingAstVisitor, AbstractAstTransformer which are generated (how?) and traverse the AST in the “standard” way. Most user visitors subclass one of these (e.g. AbstractAstVisitor), override some methods and in the end always call base to continue the traversal.

Used on many places for many things. Code conversions are a neat feature in the past but not maintained anymore.

#### Parser

cs.atg -> Coco -> CSharp.Parser (partial class calling methods of its second part written by hand)

#### Lexer

Written by hand in Lexer.cs.

### ICSharpCode.SharpDevelop.DOM – maybe remove, will be replaced

Type system representation:

IEntity <- IClass (has members), IMember <- IMethod (which has parameters), etc. In SharpDevelop they represent both user’s types and types loaded from referenced assemblies.

IReturnType is a reference to a type. IReturnType.GetUnderlyingClass() returns the IClass this type represents. Can also be a ConstructedType, e.g. List<string> which doesn’t “exists” anywhere and then GetUnderlyingClass returns null.

Entities converted to string representation by IAmbience.

IExpressionFinder.FindExpression returns ExpressionResult: string + location + context (e.g. AttributeContext).

IResolver.Resolve takes the ExpressionResult and returns ResolveResult (e.g. TypeResolveResult which contains the resolved IClass, MemberResolveResult which contains the resolved IMember, UnknownIdentifierResolveResult, UnknownMethodResolveResult, etc).

### New NRefactory for SharpDevelop 5.0

Will replace NRefactory and DOM. Short explanation and link to github.

ExpressionFinder will be replaced by keeping the AST + looking up the node.

### The editor

### Language bindings

### Project system

IProject. MSBuildBasedProject is the base, does loading using Microsoft.Build.

### Debugger

SharpDevelop’s integrated debugger consists of two components – Debugger.Core and Debugger.AddIn. Debugger.Core is a standalone debugging library for .NET and Debugger.AddIn integrates this library into SharpDevelop. Essentially, Debugger.AddIn *is* the integrated debugger and Debugger.Core is the underlying library.

The author of both Debugger.Core and Debugger.AddIn is David Srbecký.

#### Debugger.AddIn

Debugger.AddIn is essentially SharpDevelop’s integrated debugger. It contains all of the IDE-specific logic and user interface, including the Debugger tooltips and Debugger visualizers. Debugger.AddIn relies on Debugger.Core for most of its functionality, for example setting breakpoints, stepping, or evaluating expressions.

#### Debugger.Core

Debugger.Core is a standalone debugging library for .NET. It provides features typically present in debuggers: attaching to and controlling a user program, stepping, setting breakpoints, exploring state of the variables in the program etc.

Debugger.Core uses the low-level debugging COM API provided by the .NET runtime, called ICorDebug (<http://msdn.microsoft.com/en-us/library/ms404520.aspx>).

##### Terminology

The program under the control of the debugger is called a **debuggee**.

##### Architecture

Debugger.Core consists of four cleanly separated layers. Starting from the lowest layer, these layers are:

* COM API:  The low-level unmanaged debugging API of the .NET framework.  The API contains interfaces such as ICorDebug or ICorDebugManagedCallback.
* COM wrappers:  Auto-generated thin layer over the COM API which makes it a bit easier to use.  It converts 'out' parameters to return values and tracks returned COM objects so that they can be explicitly released (this is necessary so that the debugger does not lock assemblies).  The layer also contains several hand-written methods that handle marshaling of strings and other objects.
* NDebugger:  The debugging library itself.  It provides access to variables and types via reflection-like interface.  It provides commands for setting breakpoints, stepping and basically everything usually expected from a debugger.
* ExpressionEvaluator:  Extension on top of NDebugger which can evaluate C# expressions.  ExpressionEvaluator depends on SharpDevelop's NRefactory.

##### Fundamentals of debugging – mostly copied from David

http://community.sharpdevelop.net/blogs/dsrbecky/archive/2010/07/29/debugger.aspx

The debugger can start a new debuggee process or it can attach to an existing one.  While the debuggee is running, there is not much the debugger can do.  Almost all operations are forbidden.  The debugger has to wait until the debuggee pauses - usually because user's breakpoint is hit.  Once the debuggee is paused, the debugger can investigate its state - it can look at the callstack, read local variables and so on.  Stepping or pressing "Continue" will put the debuggee into running state again. An important thing to realize is that the debugger and the debuggee are running in separate processes.

##### Sample

To demonstrate Debugger.Core in practice, let’s look at an example of its usage. Assume we have the following “Hello world” program:

class Program

{

**public** static void **Main**(string[] args)

{

string message = "Hello World!";

System.Console.**WriteLine**(message);

}

}

This program can be debugged using the following code:

NDebugger debugger = **new NDebugger**();

Breakpoint breakpoint = debugger.**AddBreakpoint**("Program.cs", 6);

breakpoint.Hit += delegate { MessageBox.**Show**("Breakpoint hit"); };

// Start the debugee

Process process = debugger.**Start**("HelloWorld.exe", "C:\\", **null**);

// Waits until the breakpoint is hit if it did not

// already happen.

process.**WaitForPause**();

// The breakpoint hit message should be shown now

// Show the name of the current method on the stackframe

MessageBox.**Show**("Current method = " + process.SelectedStackFrame.MethodInfo.FullName);

// Get reference to the local variable

Value localVariable = process.SelectedStackFrame.**GetLocalVariableValue**("message");

MessageBox.**Show**(string.**Format**("message = {0} (type: {1})", localVariable.AsString(), localVariable.Type.Name));

// Resume execution after the breakpoint

process.**AsyncContinue**();

The program produces the following messages:

• Breakpoint hit

• Current method = Program.Main

• message = Hello World! (type: String)

##### Investigating state of variables

The sample code in the previous section showed that it is possible to obtain values of variables defined in the debuggee process. This section described how the process of obtaining values of variables works and what the design decision were when building this part of the debugger API.

###### Values

The sample code in the previous section (link) showed a statement for obtaining the value of a variable:

Value localVariable = process.SelectedStackFrame.**GetLocalVariableValue**("message");

MessageBox.**Show**(string.**Format**("message = {0} (type: {1})", localVariable.AsString(), localVariable.Type.Name));

The object returned by the GetLocalVariableValue call is of type Debugger.Value. The Value class has an AsString() method which returns a string representation of the value of the variable.

What exactly is the Value? As said before, the debugger and the debuggee are running in separate processes. That means the Value cannot hold a direct reference to the value in the debuggee process (because memory spaces of individual processes are strictly separated by the operating system). Instead, some sort of interprocess communication must be used. The ICorDebug API used by the Value class under the hood takes of this.

If the value is of primitive type like string or integer, its actual content can be requested.  However if the value is a class, we must enumerate its fields and properties and get the values for the ones that we are interested in.  We are of course free to get fields of the new values as well and drill down as much as we want to.

There is a good reason why this model is appropriate.  When the debugger's code was compiled, it did not know that the user will create a field "myHelloWorldMessage" and therefore it could not reference it.  Even if direct reference to the object in the other process was somehow available, the debugger would still have to use reflection to figure out what fields the object contains and then get their values one by one.  In fact, most of the debugger's API inherits from the abstract reflection classes (like Type, MethodInfo) so anyone familiar with reflection should have no problems using the debugger API.

###### Lifetime of Values

The .NET garbage collector (GC) presents a significant complication to the debugger.  When the debuggee is paused no code can be executed including the garbage collector so it is safe to investigate it as much and as long as we want.  However, if the debuggee is resumed even for just a few instructions, the GC might have been run and it might have moved all variables around in memory.  The GC takes care to update all references within the debuggee so that it does not even notice.  However, it unfortunately does not tell the debugger.  This means that whenever the debuggee is resumed, all debugger's Values become invalid because they might be pointing to wrong memory (Value holds a reference to the COM object identifying the value in the debuggee).  The next time the debuggee is paused, it has to obtain all values again.  This problem is more problematic than it might initially seem - getting a value of a property or calling Object.ToString() both require that the debuggee is resumed for a while so that the methods can be injected into the debuggee and executed.  Imagine that we are debugger tooltips to drill down to object "foo.bar.Person" which contains two properties - FirstName and Surname.  After we evaluate the "FirstName" property, all values will become invalid and we will have to obtain "foo.bar.Person" again just so that you we evaluate "Surname".

###### PermanentReferences

The ICorDebug API provides a facility to get around the problem with the lifetime of Values – it is possible to create a strong handle, which does not become invalid when the debuggee is resumed and always points to the right place in the memory where the debuggee instance resides, even after the target instance was moved by the garbage collector. This functionality is accessible using the Value.GetPermanentReference() method in Debugger.Core. In this thesis, we call Values returned from GetPermanentReference() *Permanent references*.

It seems that the problem with the lifetime of Values is solved by immediately obtaining a Permanent reference immediately when obtaining any Value. However, the documentation states that user code should never keep many Permanent references (more than a few hundred). Therefore, the problem remains as we are allowed to create Permanent references and use them shortly but we cannot keep many of them as long as we need to.

###### Expressions

To get around the problem with Garbage collection invalidating Values, Debugger.Core provides **expressions**. Expression represents a way to obtain Value, for example "foo.bar.Person“. Expression itself is not stored in the string form, but as a tree. Actually, Debugger.Core uses NRefactory Expressions to represent expressions.

Expressions can be turned into their string representation (e.g. "foo.bar.Person“) and parsed from a string in C# format. This functionality already comes from NRefactory.

Expressions can be Evaluated using Expression.Evaluate(), producing a Value. That makes them very useful – instead of keeping a Value and never knowing when it becomes invalid, we keep an expression an evaluate it whenever we need its value. Indeed, this how all the debugging UI of SharpDevelop uses the expressions: When the user has "foo.bar" open and expands "Person", SharpDevelop first generates the expression "foo.bar.Person" and then evaluates it.

At one point in the past, the Value class was designed so that it would remember the expression using which it was obtained and automatically reevaluate itself if needed.  However, this approach turned out to be quite difficult to debug since a relatively simple call could cause complicated chain of events.  The expression based approach is more explicit and thus allows better reasoning about the program - both in terms of behaviour and performance.

###### Expression evaluation

The Debugger.Core uses NRefactory Expressions to represent expressions to be evaluated and expression evaluation is implemented in the ExpressionEvaluator class which is a Visitor. This makes a lot of sense since the evaluation can be defined recursively:

For example, when evaluating expressions *list[i+3].Name* or *person.Name*, *list[i+3]* or person is evaluated first and then the field or property called Name is evaluated on the result of the evaluation. To evaluate *list[i+3]*, *i+3* has to be evaluated first and finally the indexer is evaluated, passing in the result of the evaluation of *i+3* as a parameter.

This is exactly how the ExpressionEvaluator visitor works. Methods are also supported (so „foo.Bar(foo).Foo“ can be evaluated).

Caching

Performance tricks

There are some clever tricks used to improve performance of the evaluation. For example, in .NET it is very common to have properties with getter methods just returning a backing field, such as (in C#).

string Name { get { this.name; } }

or

string Name { get; set; } // backing field is generated by the compiler

Exploiting the fact that getting values of fiels is much faster that using getters (which requires resuming the debuggee and waiting for result), the value of the field is returned directly when possible.

This is done by looking at IL of the getter method to see if it is a method in the form „return field;“. Such IL can have four different versions when generated by Microsoft’s C# compiler (depending on the property being instance/static and the backing field being explicit/generated). Here is the code to recognize all these four versions (can be found in DebugMethodInfo):

(**Read**(code, 0x00) || **true**) &&                      // nop || nothing   
(**Read**(code, 0x02, 0x7B) || **Read**(code, 0x7E)) &&   // ldarg.0; ldfld || ldsfld  
**ReadToken**(code, **ref** token) &&                      //   <field token>  
(**Read**(code, 0x0A, 0x2B, 0x00, 0x06) || **true**) &&    // stloc.0; br.s; offset+00; ldloc.0 || nothing  
**Read**(code, 0x2A);                                  // ret

##### The type system

The debugger can not only provide information about the values in the debuggee, but also about their types. In fact, to be able to obtain contents of a complex value (instance of a class) we must know the type of the value to be able to iterate its fields and properties and get their values one by one. This is a very common pattern used everywhere in SharpDevelop, including our visualizers.

The API provided by the debugger to investigate the types in the debuggee is very easy to understand if one is familiar with Reflection. In fact, the API is exactly the same as reflection. The class DebugType implements the abstract class System.Type, so it has methods like GetProperties() and GetMethods() which return System.Reflection.PropertyInfo, MethodInfo etc. They actually return debugger-specific implementations of these types but that is not a concern to the user.

Again, under the covers, the debugger uses the low level COM API provided by the .NET runtime (for example the IMetadataImport interface).

##### Multithreading

Unfortunately from the specification of the underlying ICorDebugAPI, all the debugger calls have to be invoked from the main thread. Evaluating multiple expressions at once would be a performance improvement for some parts of the code working with the Debugger API (including the Debugger visualizers) but this is not possible.

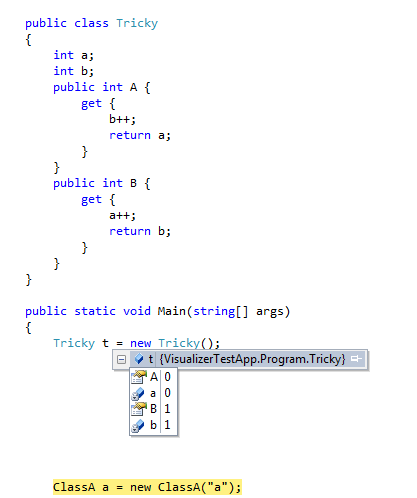
##### Evaluating multiple values at once

In the code of SharpDevelop’s Debugger.AddIn, one can notice a very common pattern – the values of fields and properties

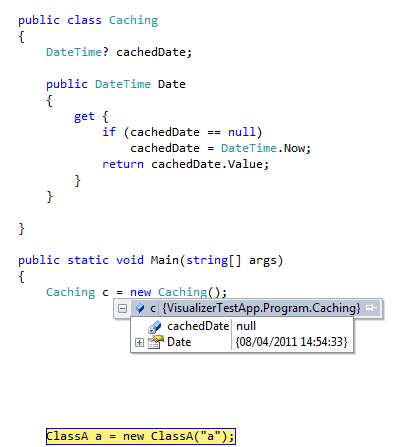
## Fundamental problem of debugging

Interesting – talk about two properties changing each other. Getter of A increments B and vice versa. Debugger not only changes the state of the program, but also displays incorrect state.

public class Tricky  
{  
 int a;  
 int b;  
 public int A {   
 get {  
 b++;  
 return a;  
 }  
 }  
 public int B {   
 get {  
 a++;  
 return b;  
 }  
 }  
}



public class Caching  
{  
 DateTime? cachedDate;  
   
 public DateTime Date   
 {  
 get {  
 if (cachedDate == null)  
 cachedDate = DateTime.Now;  
 return cachedDate.Value;  
 }  
 }  
   
}



## Division of work – OK?

In the motivation section it was stated that this thesis aims to solve issues with the current state of debugging Object graphs and Collections and to improve SharpDevelop’s debugger tooltips in the direction of collection support. As visualizing changes in object graphs and visualizing contents of collections are distinct topics, it was decided (after a discussion with the SharpDevelop team) that there will be two new separate features in SharpDevelop – the Object graph visualizer and the Collection visualizer. The third feature are the debugger tooltips. The debugger tooltips will conceptually stay the same as they were in SharpDevelop 3, but will be re-implemented in WPF with added proper support for debugging collections. This thesis will analyze the Object graph visualizer, the Collection visualizer, and the Debugger tooltips mostly separately but it will also identify common functionality shared by these three features – such as collection support.

## Collections

From the goals set for the Collection visualizer and Debugger tooltips, it is clear that both of them will handle collections – the Debugger tooltips need support for IEnumerable collections and large collections and the Collection visualizer will handle the same types of collections as well. As for the Object graphs – the individual nodes in actual object graphs can, indeed, also be collections, therefore it would be best to support collections in the Object graph visualizer as well.

Screenshot same collection in all three visualizers

The common requirement for all of the visualizers is that large collections are supported without significant degradation in performance. In the previous version of SharpDevelop, when a collection variable was expanded in the debugger tooltips, the tooltips first obtained all of the collection items from the debugger and only then displayed first few items. Since the communication with the debugger has to be done on the main thread (as discussed in the section about the debugger), the whole IDE was blocked for up to minutes, depending on the size of the collection.

This thesis takes (we take?) a lazy approach to getting the items of collections from the debugger – since only the first few items are displayed, only these are obtained. As the view is scrolled, more items are being pulled from the debugger. This approach can be applied to all of the visualizers.

### Types of collections

The basic inheritance hierarchy of .NET collection interfaces is the following.



Make a simpler diagram, with arrays. As seen from the diagram, all the collection types in .NET framework, including arrays, implement IEnumerable. Also, when dealing with user-defined collection types (including enumerators implemented using the **yield return** construct in C#), it is safe to assume that any user type that has semantics of a collection will implement IEnumerable. Therefore by supporting IEnumerable, all possible types of collections would be supported.

However, the IEnumerable interface itself is very basic – it only enables sequential iteration over the collection, without random access. The following three sections analyze possible approaches to supporting collection types in the visualizers. Prvni 2 sekce vlastne ukazuji nedostatecna reseni, ale jsou dobre jako dokumentace postupu mysleni – OK?:

### First approach – treating all collections as IEnumerable

The starting point for all the visualizers is a Debugger.Value or a Debugger.Expression (which, when evaluated, yields a Value). First, it must be verified that the debuggee instance represented by the Value implements System.Collections.IEnumerable, which can be done by examining Value.Type.FullName. Then it is possible to obtain the individual Values representing the items: the method “GetEnumerator()” is invoked and the result is stored as a Permanent reference. Then, whenever the collection view is scrolled and more items are needed, the “MoveNext()” method and “Current” getter are invoked on the enumerator object to obtain a Value representing the next item. When “MoveNext()” returns false, there are no more items available.

#### Pros

* One implementation supports all types of .NET collections.
* Supports infinite collections. It is not a problem if MoveNext() never returns false - first few items will be displayed immediately and more and more items will be obtained as needed.

#### Cons

There are several Cons to the generic IEnumerable solution with important implications which deserve a dedicated section.

##### Expanding individual items

A very important requirement in all of the visualizers is that the individual items of collections can be expanded further. To expand an item, an identification of the item is needed – either a Debugger.Value or a Debugger.Expression. For Values obtained from an enumerator, there are no corresponding Expressions – the instances returned from the enumerator can be new objects which cannot be reached through any variables in user code simply because the user code does not reference the instances. The only remaining possible identification of the Values returned obtained from the enumerator are therefore the Values themselves, in form of Permanent references (because without Permanent references they would all become invalid immediately when obtaining the next item). The problem is that scrolling the view of the collection would cause more and more Permanent references to be kept and, by specification, holding many Permanent references is not allowed.

The only solution possible here would be not to hold any identification of the Values and when an item at index i is expanded, iterate over the collection from the beginning (by obtaining a new enumerator) to the i-th item and expanding it. Such solution would not be very efficient and moreover, the item obtained by re-enumerating the collection could be a different instance from the one which is being expanded.

##### The length of the collection

Working with IEnumerable means that there is no way to tell how many items the collection contains which means that users will never know how many items there are in the collection. A scrollbar can be displayed, but it will not reflect the actual state accurately. The actual length of the IEnumerable could be determined by invoking System.Linq.Enumerable.Count(IEnumerable<T>) but it cannot be guaranteed that the debuggee references System.Linq.

##### Fast scrolling

Having to access the items IEnumerable collections sequentially means that scrolling the collection view faster than the items can be obtained from the debugger will not be possible.

#### Summary

The cons of the IEnumerable solution are significant and it can be observed that all of them are caused by the simple nature of the IEnumerable interface allowing only sequential access to the items. The problems with determining the length of the collection and fast scrolling cannot be resolved. Expanding can be solved only partially by re-enumerating the collection always from the beginning, possibly obtaining wrong instances. The Pros of this solution are outweighed greatly by its Cons.

### Second approach – special case for IList

In the .NET collection interface hierarchy there is an interface called IList which adds an indexer allowing random access to the items. This section explores the possibilities of dealing with collections when the collections also implement IList. It can be verified that a Value implements System.Collections.IList by examining Value.Type. The individual items from the IList can be obtained by invoking the indexer getter on the Value representing the whole IList instance. This approach is almost equivalent to evaluating expressions such as “list[i]” where “list” is the name of the IList variable in the debuggee, with the exception that it also works when the whole IList was obtained from an enumerator and therefore has no Expression.

#### Pros

* Expanding individual items is not a problem: to expand an item at position *i*, it is sufficient to remember the Permanent reference representing the whole IList and invoke the indexer on this Permanent rerference, passing *i* as a parameter.
* The length of the collection is immediately known by evaluating the “Count” property on the IList Value. A scrollbar of correct size can be displayed.
* There are no limitations on the speed of scrolling. If properly implemented, it will be possible to skip evaluation of items which are being scrolled over fast.

#### Cons

* Works for IList but not for IEnumerable.

#### Summary

The Pros of making a special case for IList are so significant that it is definitely worth it to support IList separately. When an instance does not implement IList and only implements IEnumerable, a fallback to the basic IEnumerable solution can be implemented.

### Third approach – converting IEnumerable to IList

There is another possible approach to IEnumerable which is not immediately obvious – having an expression “e” representing an IEnumerable<T>, by evaluating an Expression “new List<T>(e)”, the IEnumerable<T> gets fully enumerated directly in the debuggee (as fast as if the debuggee itself called “new List<T>(e)”) and a Value representing the new List is returned. Then the visualizers can work with the List, enabling expanding, accurate scrollbar, and fast scrolling. The constructor of List<T> is always available because List<T> resides in mscorlib.dll which is always loaded in any .NET process (mscorlib defines all the system types, like System.Int32 or System.String).

The solution is then to visualize ILists using the Second approach and visualize IEnumerable<T> by converting into IList and then also using the Second approach.

#### Pros

* All the Pros of the Second approach hold not only for IList and IList<T>, but also for IEnumerable<T>.

#### Cons

* This solution cannot be applied to non-generic IEnumerable collections. Unfortunately, there is no method in .NET 2.0 mscorlib (we want to support .NET 2 programs) that accepts non-generic IEnumerable and returns an IList.
* Infinite IEnumerable<T> collections are not be supported – the evaluation will timeout.

### Conclusion

From the three approaches, the last one was chosen to be used in all of the visualizers. It has very strong Pros only at the cost of not supporting non-generic IEnumerable and infinite collections, which are both rare cases. To support these two cases, the fallback to the first approach can be implemented, but it was decided not to do so – it would mean maintaining more code only two support two uncommon cases which arguably most programmers almost never encounter (actually we had the First approach implemented but removed it for maintainability reasons – the First approach works with Values while the Third approach enables working with Expression consistently everywhere).

Note: Experiments with Visual Studio 2008 show that its integrated debugger timeouts when expanding an infinite IEnumerable collection in a debugger tooltip. This indicates that the Visual Studio debugger is probably an approach similar to our Third approach.

#### Expression caching

The visualizers will be getting the individual collection items by evaluating Expressions such as “list[i].Name”. In the section about Expression evaluation (link), it was stated that the ExpressionEvaluator internally caches Permanent references to evaluated expressions. This means that when scrolling a view of a collection, more and more Permanent references would be held by the Expression cache. To solve this problem, after a discussion with David Srbecký a method to clear the Expression cache was added to Debugger.Core and the visualizers will call this method periodically to avoid holding many Permanent references when working with large collections.

## Object graph visualizer

The high level picture of the Object graph visualizer is the following:

The user enters an expression to be visualized. The visualizer explores the object graph starting at this expression and presents it to the user in a similar way people draw data structures on a whiteboard. When a step in the debugger is performed, the drawing of the graph is updated using a transition from the old state to the new state. The transition should help users understand the changes that occurred.

### Existing work

There have been attempts to implement something similar. Probably the most significant effort so far has been the Data Display Debugger (<http://www.gnu.org/software/ddd/>) which is a graphical frontent to the command line debuggers like GDB or a Python debugger pydb. Unfortunately, none of these debuggers support debugging managed .NET programs.



### What needs to be done

Let’s take a high level look at what needs to be done. We want an object graph for a given expression to be presented to the user in a similar way people would draw the object graph on a whiteboard. Can the task be split into separate parts / steps? Yes it can, at least into these two steps:

1. Building the graph - given an expression, determine the vertices and edges of the graph
2. Drawing the graph

The second step (drawing) can be split into two independent steps:

* Determining the layout of the graph (that is the positions of nodes and edges on a plane)
* The actual drawing to the screen

The last required feature are the transitions which visualize the changes caused by steps in the debugger. This leaves us with:

1. Graph building
2. Graph layout
3. Graph drawing
4. Graph transitions

The first three steps can be done independently but what about the Graph transitions? Will Graph transitions be a completely separate step or will they interact with Graph building / layout / drawing?

#### Graph transitions

To decide how Graph transitions integrate with the rest of the algorithm, one has to realize how debugger steps work. During a debugger step, a temporary breakpoint is placed at the location of the next code segment, the debugge is resumed to run at full speed until it hits the breakpoint. When the temporary breakpoint is hit, the control is returned to the debugger.

Graph transitions should visualize the change caused by the debugger step, by moving existing nodes to their new positions, and making it clear which nodes have been added and removed. A natural idea would be to obtain some kind of a diff from the debugger describing the changes which occurred and based on this diff then produce the transition. Unfortunately, the debugger has no control over the debuggee while the debuggee is running and obtaining such state diff directly is not possible.

However, we propose that it is still possible to infer a diff based on observations of the debuggee state before and after the step. After the debugger step is finished and the control is returned to the debugger, a new Object graph is built, reflecting the current state. The instances found in this new Object graph are compared to the instances found in the old Object graph from before the step and as a result of this comparison, a diff describing the changes is obtained. Using this diff a graphical transition explaining the changes can be produced. More details can be found in a dedicated section (forward link?).

The conclusion to this section is that Graph building, Layout and Drawing will not depend on Graph transitions. Graph transitions will use the information obtained in the Graph building phase to infer a diff between two Object graphs and produce a graphical transition from the first graph to the second one.

### Graph building

Definition: Object graph is an oriented graph, where vertices represent in-memory instances. Let vA and vB be two vertices representing two instances A and B. There is an oriented edge from vA to vB if and only if instance A has a direct reference to B (through a field or a property).

The problem: Given a reference to an instance in the debuggee, build an object graph representing all instances reachable from this instance (up to a maximum depth in case the graph is too large).

#### The algorithm

We propose the following algorithm to build an object graph given an expression e. The algorithm is quite straightforward – it does a DFS walk down the object graph in the debuggee, checking for already seen nodes. The checking for already seen nodes is done by the function GetSeenNode which is a crucial because it enables detecting shared references and loops correctly. The result is a graph having the same “shape” as the object graph in the debuggee (in other words the graph built by this algorithm is isomorphic to the actual graph in the debuggee).

value = **Evaluate**(e) // evaluate the Expression e using the debugger to obtain a Value

graph = BuildGraph(value) // build the graph

// value is a Debugger.Value representing an instance in the debuggee process

**BuildGraph**(value):

If a maximum recursion depth is reached, return null.

node = create a new graph node representing this value

// get all Values (instances) that this Value points to

foreach referencedValue in **GetReferencedValues**(value)

// do we already have a node reprenting the referenced instance?

existingNode = **GetSeenNode**(referencedValue)

// if yes, add an edge to this node

if existingNode != null then MakeEdge(node, existingNode)

// otherwise continue recursively

else MakeEdge(node, **BuildGraph**(referencedValue))

Will this be possible to implement? The calls Evaluate and **GetReferencedValues** will need to access the debugger API. Both of them will be possible to implement using the debugger API: Evaluating expressions as well as enumerating and fields and properties of objects is supported. What actually makes the Object graph special is the function GetSeenNode. Without this function the algorithm would be equivalent to expanding debugger tooltips or watches recursively and wouldn’t depict the actual structure of the object graph. The main question is therefore whether and how GetSeenNode will be possible to implement.

#### Analysis of GetSeenNode

In the algorithm link, the GetSeenNode function takes a reference to an instance in the debuggee (a Debugger.Value) and returns a graph node that has been already created for this instance, or null if such node doesn’t exist in the graph yet.

To be able to distinguish which Values have been seen from those which haven’t, the algorithm will have to keep some unique identifiers of the Values. Another option would be to add some extra information directly to the instances in the debuggee, but that is not possible, as in .NET it is not possible to add fields to objects at runtime\* (\*It is be possible to create a Dictionary in the debuggee, but Dictionary uses overridden equality – not instance equality. A section on this?). Not being able to add unique identifiers to the instances in the debuggee process means that unique identifiers have to be added to the Values living in the debugger process. Permanent references represent one possible unique identification method. Expressions represent another possibility because, when evaluated, they also uniquely identify Values. As it will be shown, Permanent references and Expressions are mostly interchangeable for the purposes of building the Object graph.

A first solution, using Expressions, follows. The main algorithm works with Expressions and keeps an Expression for every node in the graph. GetReferencedExpressions creates Expressions by appending all field and property names to given Expression, based on the actual type of the Expression, (the Type is determined by evaluating the Expression). For example by appending the property name “FooProp” to object “foo.bar” we get an expression “foo.bar.FooProp”.

**BuildGraph**(expression):

If a maximum recursion depth is reached, return null.

node = create a new graph node representing this expression

foreach referencedExpression in **GetReferencedExpressions** (expression)

existingNode = **GetSeenNode**(referencedExpression)

if existingNode != null then MakeEdge(node, existingNode)

else MakeEdge(node, **BuildGraph**(referencedExpression))

When GetSeenNode then is to determine whether an Expression identifies an already seen instance, it queries the debugger to compare the Expression to all of the seen Expressions (by evaluating Expressions such as “foo.bar.Name == e”, where e is replaced by all the expressions seen so far, such as “foo.bar” etc.). This works because an expression “a == b” evaluates to true if an only if expressions *a* and *b* refer to the same instance in the debuggee, because evaluating an expression “a == b” is equivalent to executing “a == b” in the debuggee.

**GetSeenNode**(Expression exprToTest)

foreach node in graphNodesSoFar

if **Evaluate**(BinaryOperatorExpression(op.Equals, node.Expression, exprToTest))

return node

return null

As can be seen from the pseudocode, every call of GetSeenNode has to do many Evaluate calls, which is the most significant problem of this algorithm. Since GetSeenNode will be called once per edge and it needs do up to **n** Evaluate calls, the total number of Evaluate calls in O(n.E) where **n** is the size of the resulting graph and **E** is the number of edges in the graph. We implemented this algorithm first and found it to be too slow. Even though the graphs to visualize will usually not be very large, the Evaluate calls are unfortunately so expensive that this algorithm is inacceptable.

The algorith using PermanentReferences would be exactly the same, including the needed calls to the debugger in a loop, expect it would work with Permanent references. Permanent references also provide instance addresses (offsets in the memory space of the debuggee) but these are not usable as they can be changed by the garbage collector which mvoes the instances around during the run of the graph building algorithm, when the debuggee is being resumed and paused again. Therefore, addresses cannot be used as unique instance identifiers and the only way to use Permanent references is the same way as using Expressions.

From the discussion so far it can be immediately concluded that the main problem with identifying debuggee instances by Expressions or Permanent references is that GetSeenNode has to compare all the unique identifiers one by one by querying the debugger. The best solution to this problem would be some different form of unique indetification of an instance in the debuggee such that GetSeenNode could run faster than in O(n), ideally in O(1) in average case.

##### .NET hashcodes

Can standard .NET hash codes serve as unique identifiers in the Object graph building algorithm?

In .NET, every object has a standard hash code assigned by the runtime environment, accessible by the method RuntimeHelpers.GetHashCode() (we are not interested in the standard Object.GetHashCode() because that has the semantics of user-defined instance equality and the Object graph should r true instance equality). Regarding the Object graph building algorithm, the hash codes have a good property that they never change during the lifetime of an instance and, being integers, they can be used as keys for a hash table (they even should be reasonably distributed).

However, there is no guarantee that the hash codes will be unique – there is no guarantee that two different instances will have different hash codes. The “theoretical” reason behind this is that the hash code is a 32-bit integer, hence the space of all hash codes is limited and it can be guaranteed that sooner or later two different objects with the same hash code will be encountered. There is, however, one very practical reason. One could think that 32-bit space is large enough and in practice different instances with same hash codes would almost never be encountered. However, our tests on CLR (Microsoft’s implementation of CLI) are quite surprising. The following code generates new objects until two different objects with same hash code are encountered. It turns out that such case occurs very quickly, after creating as few a few thousand instances instances:

Hashtable hashCodesSeen = new Hashtable();    
LinkedList<object> l = new LinkedList<object>();    
int n = 0;  
while (true)    
{    
    object o = new object();    
    // remember object so that they don't get collected    
    // this does not make any difference though :(    
    l.AddFirst(o);    
    int hashCode = o.GetHashCode();    
    n++;    
    if (hashCodesSeen.ContainsKey(hashCode))    
    {    
        // same hashCode seen twice for DIFFERENT

Console.WriteLine("Hashcode seen twice after „ + n + „steps“);    
        break;    
    }    
    hashCodesSeen.Add(hashCode, null);    
}

During our tests, the ouput of this code was “Hashcode seen twice after 5322 steps.” These results seem surprising, but when thought our carefully, they make sense. Even if the hash codes were generated completely at random with a good random distribution there would still be quite a high probability of hitting one value twice after 5000 attempts (this is an instance of the birthday paradox – is it true? Exact numbers!). At the same time, trying to avoid this phenomenon could be contra-productive. For example, generating hash codes sequentially would not be a good idea as we know – hash codes should be well distributed if we want them to serve their purpose – to be keys for hash tables.

###### Hash code implementation in the runtime

In CLR, the runtime representation of every instance has a data member which stores the hash code for the instance. This data member is assigned by the CLR and it is accessible from managed code through RuntimeHelpers.GetHashCode(Object) method which returns the same value as the default Object.GetHashCode(). While Object.GetHashCode() can be overridden to define equality semantics for structures and classes, RuntimeHelpers.GetHashCode(Object) always returns the original hash code assigned by the runtime.

Note: the experiment Code from SO (ref to listing.) always ends after the same number of attempts on a given machine. This shows that the hash code generation is deterministic on the current CLR implementation.

#### The final algorithm

The final Object graph building algorithm takes advantage of the .NET hash codes while correctly accounting for different instances having the same hash code. This is done by looking up Nodes by hash codes, and comparing instance addresses in case of a hash code match to be sure the hash code match is not a coincidence (each Node holds a Permanent reference to be able to access the address of the in-debuggee instance). The main BuildGraph algorithm stays almost the same as in the first version, with the exception that graph nodes are being added into a hashcode->Nodes hashtable. Ideally, when there are no hash code collisions, the hashtable will contain exactly one Node for every hash code.

hashtable: 'hashCode' -> (list of objects with hash code == 'hashCode')

**BuildGraph**(value):

If a maximum recursion depth is reached, return null.

node = create a new graph node representing this value (holding a Permanent reference)

add the node to the hashtable at key value.HashCode (where HashCode is the in-debuggee hash code)

foreach referencedValue in **GetReferencedValues**(value)

existingNode = **GetSeenNode**(referencedValue)

if existingNode != null then MakeEdge(node, existingNode)

else MakeEdge(node, **BuildGraph**(referencedValue))

GetSeenNode then takes the advantage of the hashtable in the following way:

GetSeenNode(value) {  
    candidates = hashtable[value.HashCode] // instances with same hashCode  
    if no candidates, the object is new  
    if some candidates, **compare the addresses of their Permanent references to o.Address**  
      if no address equal (the hash code was just a coincidence) -> o is new  
      if some address equal, o already seen  
}

GetSeenNode only works with Value addresses, which is safe becase getting addresses of Values does not resume the debuggee and therefore the addresses are guaranteed to be fixed during the execution of GetSeenNode.

Note: As said, the algorithm always obtains hash codes by invoking RuntimeHelpers.GetHashCode in the debuggee. If the algorithm instead used Object.GetHashCode() and the user code would override GetHashCode to always return zero (for example), the algorithm would still work. The whole algorithm would, however, run in O(n.E) (n being the number of vertices and E being the number of edges in the object graph) – the same as the original slow algorithm.

#### Expanding nodes

The graph building algorithm as described can be considered finished. It handles very large (up to infinite) graphs by limiting the maximum depth of recursion.

There is, however, one user experience aspect that deserves analysis - when the user enters an expression which evaluates to a very large object graph, expanding the whole graph up to some maximum depth would be a bad user experience:

* If the maximum depth is small, nodes the user is actually interested in can be missing from the graph.
* If the maximum depth is large, too many nodes are shown while the user is not interested in most of them; the drawing is confusing. Visualization takes too much time to show nodes that are not needed.

Instead of always traversing the whole graph, a solution is proposed where users can choose which nodes to include in the graph by expanding them manually. The algorithm stays essentially the same but it is split into steps determined by user actions. The body of the Expand function called when a Node is being expanded is the same as the body of the original loop iterating over all Node properties.

// a property is being expanded on this node

**Expand**(node, propertyName)

// get the value of the property being expanded

targetValue = EvaluateProperty(node, propertyName)

// and add the value to the graph (either an edge to an existing node, or a new node)

existingNode = **GetSeenNode**(targetValue)

if existingNode != null then MakeEdge(node, existingNode)

else MakeEdge(node, **NewNode**(targetValue))

next paragraph – OK?:

The algorithm does not recalculate the whole Object graph on every Expand action – it assumes that property getters don’t have any side effects on the rest of the graph, which is a reasonable tradeoff between graph correctness and expand performance. Having property getters modify other properties is rarely done in practice – the only reasonable use case is when a property getter caches a value in a field or a data structure. Such scenario would be solved by reevaluating all the properties of the instance instead of evaluating a single property. In principle, property getters could modify also anything in the any other instances of the graph, but that would a very bad programming practice and it is practically never done, therefore it was decided not to make the general case much slower in order to account for a theoretical edge case.

Of course, apart from Expanding, there will be also a Collapse feature, which consists of removing the target Node and all its inbound and outbound edges from the graph.

### Graph layout

Having the Object graph (that is, a graph inside the debugger isomorphic to the actual graph in the debuggee) built, this section focuses on how to position the vertices and edges of the Object graph on a 2D plane so that it looks *natural* to users.

#### Dynamic graphs and incremental stability

There is one special requirement to the Graph layout – the Object graph visualizer deals with *dynamic* graphs, which directly relates to the Graph transitions feature.

There is a problem with calculating layout for dynamic graphs – if the layout algorithm does not account for graph dynamicity, **a small change to the graph can cause drastic changes to the layout**. Say for example that one node or edge is added to the graph and most nodes are rearranged completely in the new layout. In other words, such layout is *incrementally unstable*. In our scenario, incremental instability would mean large groups of nodes moving around randomly when a debugger step introduces only small changes to the graph, which would certainly mean bad user experience. The solution should therefore aim for incremental stability of the layout.

#### Existing layout engines

Graph layout is a not a new problem so naturally, existing solutions were researched. A good comprehensive list of graph layout engines can be found at <http://blogs.msdn.com/b/saveenr/archive/2009/07/29/a-list-of-tools-for-automatic-graph-and-diagram-layout.aspx>. The list does not include Dynagraph, which was also considered. As SharpDevelop is LGPL-licensed free software, any commercial solutions were out of question. Apart from being free, any code included in SharpDevelop must come from a live, maintained project.

Most of the layout engines also handle rendering of graphs. However, the Object graph visualizer has a special requirement for graph transitions, where existing nodes move to their new positions after the graph is changed. The visualizer needs to control these transitions and to be able to do so, the information about the positions of individual nodes is needed – if the layout engine acts as a black box producing images, it might be well usable in some scenarios but not for the Object graph visualizer.

Out of all the existing layout engines, only Graphviz and Dynagraph were considered an analyzed in detail. All the other layout engines were ruled out quickly - the following table shows the reasons.

|  |  |  |  |
| --- | --- | --- | --- |
| **Layout engine** | **free** | **maintained** | **suitable** |
| Graphviz |  |  |  |
| MAGL | x |  |  |
| ILOG Diagram for .NET | x |  |  |
| Dynagraph |  | x |  |
| Diagram.NET |  | x |  |
| Omnigator |  | x |  |
| Pajek |  | x |  |
| Piccolo |  | x |  |
| Flare |  |  | x (Flash) |
| UbiGraph |  |  | x (client-server) |
| aiSee |  |  | x (low quality output) |
| Graph# |  |  | x (did not exist at the time of our research) |
| Circos |  |  | x (only circular layouts) |
| Cytoscape |  |  | x (standalone app, not a library) |
| Treemaps |  |  | x (Java) |
| QuickGraph |  |  | x (graph algorithm library, does not deal with graph layout) |
| NodeXL |  |  | x (implemented in Excel) |

##### Dynagraph

Dynagraph (http://www.dynagraph.org) is an incremental layout engine based on the code of Graphviz. Being an incremental layout engine means that it is actually designed to work with dynamic, incrementally changing graphs. Dynagraph is a standalone executable with an API which works by writing text commands to standard input and parsing responses from standard output (there is also a partial, undocumented COM interface).

###### Pros

Dynagraph is the only layout engine which deals with *incremental* layouts by accepting commands such as “add edges between nodes A and B” and responding in the terms of “node B moved down by 2cm, added edge A->B as a straight line” (<http://www.dynagraph.org/documents/dynagraph.html>).

###### Cons

Dynagraph is an unmaintained library (last update 2007), which makes it unfortunately not suitable for being used in SharpDevelop.

##### Graphviz

Graphviz (<http://www.graphviz.org/>) is a mature, widely used graph layout and visualization toolkit. Graphviz consists of set of executables (dot, neato, etc.) where each of these implements one particular layout algorithm. All of the executables act as batches accepting command line parameters and standard input and returning results (text, image) to standard output.

Graphviz provides ways for users to control the layout to some degree using node clusters, explicitly specified edge endpoints etc. The following graph, which looks almost exactly like what the Object graph visualizer should look like, was rendered using Graphviz:



###### Pros

The output of dot layout algorithm (picture link) seems suitable to the needs of the Object graph visualizer.

Graphviz separates layout calculation from rendering, which means that a graph (plain vertices and edges) can be passed to Graphviz and the same graph with added position information is returned. There are several formats in which the result can be returned, configurable using command line switches.

Graphviz is fast – for the purposes of the Object graph visualizer where the graphs are not very large (up to 20 nodes and 60 edges), the time needed to calculate graph layout including launching the dot executable was under 200ms on a modest machine.

###### Cons

As Graphviz does not have any notion of dynamic graphs, its layouts can suffer from incremental instability – when a graph is slightly changed by a debugger step and the layout is recalculated, the layout can differ a lot visually from the previous layout. Graphviz does not provide any option to calculate new layout incrementally based on old layout and a graph diff.

Including Graphviz binaries would add 10MB to the size of SharpDevelop installer, while the whole SharpDevelop setup is currently only 15MB. The problem is that the Graphviz executables statically link a lot of other libraries and even when dot.exe or neato.exe are given parameters specifying text-only input and output, these executables won’t start without libraries for image encoding. This point alone is enough to say no to Graphviz because adding 10MB of binaries to SharpDevelop to support a single feature is unacceptable. The solution would be either to modify Graphviz code or ask users to install Graphviz on the fist use the Object graph visualizer.

Graphviz API is text based – using Graphviz from an application means launching a separate executable, writing graph specification to the standard input, and parsing response from the standard output. If a rendering of the graph is needed, Graphviz can write the output to a file and the host application can then read the file.

#### Conclusion – Tree layout algorithm

The conclusion of our research about existing graph layout engines is that no existing solution fits the scenario of the Object graph visualizer for SharpDevelop and therefore a new solution will be implemented.

One option is design an incremental layout algorithm which takes an existing layout and a graph diff as input and produces a new layout, trying to make only small changes to the layout when the diff is small. When designing such algorithm, methods used in Dynagraph would be studied as a starting point.

Another option is a solution which does not deal with graph diffs at all. We propose that it is possible to design a graph layout algorithm, specialized for dealing with object graphs (graphs of data structures), which has no notion of incremental layout but still produces layouts that behave well in terms of incremetal stability. The idea for the algorithm comes from two intial observations: first, object graphs are very often close to trees (the numbers of edges is not much larger than n-1, where n is the number of nodes), and second, the edges in object graphs have a special meaning – the edges represent named object properties.

The algorithm is the following: when the input graph is a tree, layout it using a standard tree layout algorithm: Place the root to the top, order the child subtrees by names of properties they represent and place the child subtrees next to each other below the root. Example: trivial picture of top-down layout.

A preudocode of the standard tree layout algorith follows. The algorithm is done in two recursive passes over the tree, which we call Measure and Arrange:

First pass: “measure”

Measure(node)

Foreach child in node.Children

Measure(child)

subtreeW = node.Children.Sum(n => n.W)

node.treeW = max(node.ownW, subtreeW);

Second pass: “arrange”

Arrange(node, position)

subtreeW = node.Children.Sum(n => n.treeW)

node.Pos = CenterHorizontally(position, node.ownW, subtreeW)

currentChildPos = position

Foreach child in node.Children

Arrange(node, currentChildPos)

// place next child subtree next to this child subtree

currentChildPos.X += child.treeW

The important case is when the input graph is not a tree. In such case, select some subset of n-1 edges to obtain a tree, layout it using the tree layout algorithm, fix the layout, and then add the remaining edges to the layout. Example: the same picture with 2 extra edges avoiding nodes.

The only thing remaining to be resolved is how to select the subset of the n-1 edges when the graph is not a tree.

##### Selecting tree edges

One possible approach is to start in the root of the graph and do a standard DFS. The edges traversed by the DFS are declared tree edges. Because the DFS enters and leaves every node exactly once, the subgraph formed by the selected edges will indeed be a tree. Preudocode follows: in the beginning, Traverse(root) is called which traverses the whole graph and marks n-1 edges as tree edges. There is a helper structure called nodeAlreadySeen used to mark visited nodes.

Traverse(node):

nodeAlreadySeen[node] = true

For each edge in node.OutgoingEdges

If not nodeAlreadySeen[edge.target]

edge.IsTreeEdge = true

Traverse(edge.target)

This approach works, but unfortunately does not behave well in terms of incremental stability – here is an example:



The problem is that when a node has multiple possible parents, DFS selects one of the parents quite arbitrarily – the paths in the graph are traversed in alphabetical order, given by the names of edges. This problem can be resolved by replacing DFS by BFS (using a queue instead of a stack to traverse the graph) because BFS selects the parent based on the distance from the root. BFS prefers short paths, not arbitrary paths. For comparison, here is the exact same situation from the previous figure, now using BFS to select the tree edges:

Screenshot

There is no strict proof that the layout generated by the tree layout algorithm using BFS for edge selection is incrementally stable because there is no strict definition of “small change of the layout proportional to the change of the object graph”. However, our tests show that in practice this is a good algorithm when dealing with incrementally changing data structures. This specific version of the tree layout algorithm also has a good property of fixed alphabetical ordering of outgoing references which is a familiar concept to users.

##### Edge routing

In the layout, not all edges are drawn as straight lines. When an edge drawn as straight line between two nodes would cross other nodes, it is routed as a curved line avoiding the nodes. Calculating the curved paths for edges is called edge routing. Graphviz provides a good edge routing algorithm but again, including 10MB of binaries into SharpDevelop is unacceptable and moreover the communication with Graphviz is done via standard input and output so a parser of edge routes returned from Graphviz would have to be implemented. We decided to implement an edge routing algorithm ourselves – the details are provided in the Implementation section.

### Graph transitions

The section about Graph layout provided a layout algorithm which is incrementally stable enough while not accounting for incremental graph updates explicitly. This section discusses how to produce smooth transitions between two layouts of two object graphs, visually explaining changes caused by a debugger step.

The transitions should move existing nodes from the old layout to their new positions in the new layout, and visually indicate which nodes were added and removed. To be able to produce such transition, it must be known which nodes from the old layout and the new layout represent the same debuggee instances, which nodes were added and which nodes were removed. We call this information a graph diff and the process of producing a graph diff is called graph *matching*.

To realize the matching, hash codes, PermanentReferences and addresses can be used, in a similar way to how they are used in Graph building. For every node in both the old and the new graph, a Permanent reference and a hash code of the debuggee instance is stored. Then for every node in the new graph a matching node in the old graph can be found quickly using the stored hash code and comparing instance addresses to make sure the hash code equality was not a coincidence. Pseudocode follows:

FindMatchingNodeInOldGraph(Node nodeInNewGraph)

find a node in the old graph by nodeInNewGraph.hashCode

if found, compare found.PermanentReference.Address and nodeInNewGraph.PermanentReference.Address

if the addresses are the equal, return the found node

This algorithms works because the hash codes of instances never change during the lifetime of instances (using RuntimeHelpers.GetHashCode). Comparing addresses in addition to comparing hash codes ensures that the found matching node represents the exact same instance (reasons were discussed in the Graph building section). The nodes from the new graph without matching nodes are marked added. The nodes from the old graph without matching nodes are marked removed. The graph diff then consists of a list of pairs of matching nodes, a list of removed nodes, and a list of added nodes. Given such diff and two graph layouts, a transition can be produced in the following way: fade out removed nodes, fade in added nodes and move matched nodes from their old positions to their new positions. The same technique can be applied to edges: edges connecting matched nodes are moved to their new positions, all the remaining edges from the old layout are faded out and the edges from the new layout are faded in.

## Collection Visualizer

The Collection visualizer should provide a new way to explore collections of objects in the debugger. It should help users understand contents of collections more easily than watches or debugger tooltips. The following solution is proposed: Display a grid where rows represent individual items of the collection and columns represent properties of individual items.

Screenshot

This advantage of this approach is that users get a good overview of the contents of the collection and can locate individual items quickly. Compare this to using watches or debugger tooltips, where individual items have to be expanded and collapsed one by one to accomplish the same goal.

The Collection visualizer will use the same approach to accessing individual items of collections described in the section Collections (link) – a special case for IList plus conversion of IEnumerable<T> to IList<T>. Therefore, the Collection visualizer inherits the properties of the solution – non-generic IEnumerables as well as infinite IEnumerables will not be supported but the number of items will be known, scrolling will be fast, and it will be possible to further expand individual rows.

### Existing work

There are some existing tools to visualize collections in the debugger in a way similar to our proposition, for example <http://davidhayden.com/blog/dave/archive/2005/12/26/2645.aspx> (a debugger visualizer for Visual Studio). However, this visualizer is designed only to visualize one type of objects specific to one application – e.g. a ShoppingCart. In other words, the visualizer is not generic.

Our collection visualizer should be completely generic – it should work for collections containing any types of objects. We haven’t found any existing generic solution which does this. (for .NET)

### What needs to be done

Summarizing the previous thoughts, here are the requirements for the Collection visualizer:

* Display contents of a collection of objects: rows represent objects, columns represent their properties.
* Support IEnumerable<T>, IList, IList<T> and one-dimensional arrays.
* Should not suffer a noticeable slowdown for collections containing thousands of items.

### Grid columns, generic vs non-generic collections

The main difference between the Collection visualizer and the Debugger tooltips is that the Collection visualizer presents values of multiple properties of all the items at once, using one column for each property. This brings us to an important question: Given a collection, how to determine what the columns will be?

If all the items of the collection were guaranteed to be of same type, it would be certainly a correct solution to make one column per each public property of this type (possibly also including properties from base classes). The problem is that the collection can, in fact, contain items of various types and it is not possible to know all these types in advance because determining them is too expensive due to the expensiveness of the debugger API calls. Realizing that it is not possible to have full information about types of all the items, there are three options:

1. Look at the first item in the collection and use its public properties.

Cons:

* The columns for the whole collection are determined only by the type of the first item.
* When subsequent items have additional properties, these properties will not be shown.
* When subsequent items miss some of the properties, the cells will be empty.

1. When scrolling and evaluating new items, add columns to the grid dynamically when new properties are encountered.

Pros:

* All of the properties of every item are always shown.

Cons:

* When items miss some of the properties, the cells will be empty.
* A complicated solution.
* Columns being added when scrolling are not a good user experience.

1. Look at the generic parameter of the collection (IList<T>, IEnumerable<T>) and use the public properties of the parameter type T.

Pros:

* The columns represent the type of the whole collection.
* Collection can contain only subclasses, therefore no cells will be empty.

Cons:

* Does not support non-generic IList (non-generic IEnumerable was decided not to be supported in general).
* When the items are sublasses of T, the properties defined in the subclass are not shown.

From the three solutions, the third one was chosen because its Cons are the least significant – non-generic ILists are not a common case (a fallback to the first solution could be implemented for non-generic ILists). Regarding the second Con: If the collection is of type IEnumerable<ICar> and the user knows that all the items are actually of type Truck, the user can add a cast to (IEnumerable<Truck>) which will cause all the properties of Truck be shown.

## Debugger tooltips

The third feature we built as a part of this thesis are the debugger tooltips for SharpDevelop 4. The goal is to re-implement the existing debugger tooltips in WPF and add support for IEnumerable collections and large collections.

### Existing work

SharpDevelop 3 has debugger tooltips implemented using Windows Forms and there is also a very similar feature in Visual Studio and other IDEs.

Screenshot SharpDevelop 3, VS, Eclipse.

### What needs to be done

The debugger tooltips in SharpDevelop 3 have cleanly separated user interface code from the underlying data model, which means the data model can be reused. Support for IEnumerable collections will be added to the data model according to the section Collections (link). The user interface implemented in Windows Forms will be removed from SharpDevelop and re-implemented using WPF.

# Implementation

This section highlights interesting parts of the implementation of Debugger visualizers for SharpDevelop and documents the codebase and design decisions.

In the SharpDevelop codebase (<https://github.com/icsharpcode/SharpDevelop>), most of the Debugger visualizers code is located in the Debugger.AddIn project (AddIns/Debugger/Debugger.AddIn folder), specifically in subfolders Visualizers and Tooltips. The code of SharpDevelop and Debugger.Core is very well designed and needed only minor modifications to integrate the debugger visualizers and debugger tooltips.

Namespaces overview

## Common base for visualizing collections

All of the visualizers are dealing with collections in essentially the same way, described in the Analysis in the Collections section. (link) The check for IEnumerable / IList implementation is implemented in TypeResolver and the conversion of IEnumerable to IList is implemented in DebuggerHelpers. Each of the visualizers has a different data model for collection items (tooltips show a tree of Expressions, the Object graph visualizer has edges outgoing from property trees, and the Collection visualizer uses a grid) but they all essentially handle collections as described in the Collections section of the Analysis.

## Object graph visualizer

In the Analysis section, the high level architecture of the Object graph visualizer was outlined. It was decided that building and layout of the graph will be separate steps, and a Tree layout algorithm, which does not work incrementally but behaves well in terms of incremental stability, was proposed. The following image shows our design depicting these decisions:



Of course, constructing a static ObjectGraph and presenting it to users is only half of the picture. As further discussed in the Analysis section, the changes which occur during debugger steps are being visualized by smooth transitions between graphs. The transitions are produced using graph diffs which are inferred by comparing graph state before and after each debugger step. The following image explains the design of the Object graph visualizer the best:

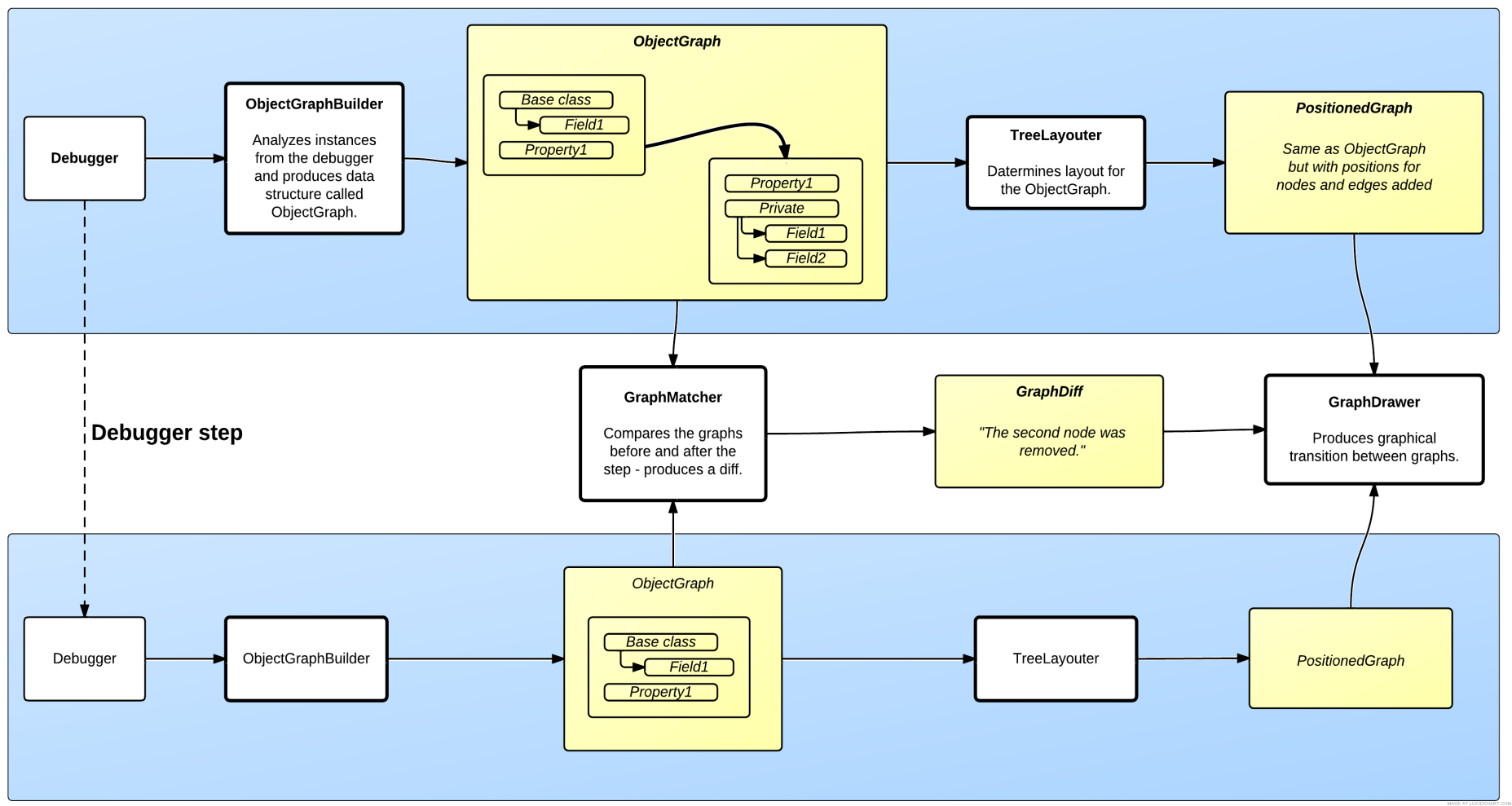


Image - Design of the Object graph visualizer.

The main window of the Object graph visualizer, from where all the processes outlined in the diagram are coordinated, is implemented in ObjectGraphControl.

Somewhere in the thesis (introduction?) mention this diagram: Debugger.Addin -> Debugger.Core -> ICorDebug and around it the boundaries of SharpDevelop and the CLR (with JITted program in it)

### Graph building

The graph building algorithm including the decisions behind it was largely described in the Analysis section. In the implementation, this algorithm resides in the ObjectGraphBuilder class. Its method BuildGraphForExpression takes a Debugger.Expression and produces an ObjectGraph.

### The ObjectGraph

* Same picture as in the overview – node contains tree of properties. Mention collection nodes

An ObjectGraphNode represents one debuggee instance and contains a tree of properties of this instance, grouping the properties by their visibility and class where they were declared. The properties are represented by PropertyNodes, each containing an ObjectGraphProperty, pointing to a target ObjectGraphNode. There also also special nodes in the property tree which serve only for grouping PropertyNodes into subtrees, like BaseClassNode or NonPublicMembersNode.

#### Lazy evaluation of properties

The ObjectGraphProperties inside ObjectGraphNodes are lazily-evaluated. When a node contains many properties, only the first few are evaluated and when the contents of the node are scrolled, the properties coming into view are being evaluated as needed.

Screenshot one node

This saves a lot of performance especially when objects have a lot of properties. The lazy evaluation is controlled by the user interface code because only the UI has exact information about which properties are currently in view. The implementation exploits the fact that WPF ListView pulls items from its ItemsSource as the items come into view. As the ItemsSource for the ListView, an instance of VirtualizingObservableCollection is used, which adds on-demand evaluation support to an existing ObservableCollection (Decorator pattern).

Class diagram

#### Collections

When an ObjectGraphNode represents a collection, the collection is converted to a List using the common approach, the Count of the List is evaluated and a flat list of empty ObjectGraphProperties is generated quickly – each ObjectGraphProperty representing one item of the List (with Expressions “list[0]” up to “list[Count-1]”). The lazy evaluation then works using exactly the same mechanism as the lazy evaluation of properties described in the previous section.

Screenshot collection

#### Expanding nodes

As discussed in the Analysis section, the ObjectGraph returned from the ObjectGraphBuilder is not fully expanded up to some given maximum depth but users control which individual nodes are expanded by clicking a “plus” button next to fields and properties.

When a field or property is being expanded, its target is evaluated and either a new node is added to the graph, or only an edge to an existing node is added in case the target was already present in the graph. Then the layout for the whole graph is recalculated. When a field or property is collapsed, its target is removed from the graph including all its inbound and outbound edges. Expanding and collapsing is implemented in ObjectGraphControl – PositionedNodeControls raise events and ObjectGraphControl reacts to them by implementing the logic just described.

##### Remembering expanded nodes between debugger steps

A large part of the design of the Object graph visualizer focuses on debugger steps. The expanding of nodes must also fit into the picture – namely, when some nodes are expanded, these nodes must also stay expanded after a debugger step. Considering the fact that after the debugger step the ObjectGraph is being rebuilt from scratch, the information about expanded nodes must be kept somewhere separately. The structure holding this information is called simply Expanded in the code. The Expanded structure holds the information about expanded nodes by holding a set of string expressions describing expanded paths in the graph, such as “a[0].left”, “a[0].left.right” etc. After a debugger step, the same paths are expanded again, which is equivalent to the user manually clicking the same “plus” buttons on the same nodes. Of course, these nodes might not represent the same debuggee instances anymore but this approach is quite intuitive and behaves as expected.

An implementation detail is that re-expanding of the right paths after a debugger step is not implemented by repeatedly invoking an Expand function but instead the expanding is incorporated right into the graph building algorithm. The ObjectGraphBuilder gets the Expanded data structure and when recursively exploring the graph, it only follows the paths which are present in the Expanded set.

### Graph layout

This section describes our Tree layout algorithm in detail. The whole layout algorithm consists of two separate steps:

* Calculating the positions of nodes (node layout)
* Calculating the paths of edges (edge routing)

Naturally, edge information is involved in the first step as well. The separation into two steps means that after the node positions are determined, the positions are fixed and only then edge paths are being added to the layout. The dot algorithm implemented in Graphviz uses exactly the same separation into two steps.

As the calculation of node positions was largely described in the Analysis section, this section focuses mainly on the algorithm for calculating edge paths.

#### TreeLayouter, PositionedGraph

The algorithms described in this sectioned are implemented in classes TreeLayouter (responsible for node layout) and EdgeRouter (responsible for edge routing). The TreeLayouter takes an ObjectGraph as input, calculates node positions, calls EdgeRouter to calculate edge routes, and produces a PositionedGraph.

The difference between ObjectGraph and PositionedGraph is that ObjectGraph is an UI-independent model of a graph of debuggee instances and PositionedGraph also contains position information for nodes and positioned paths for edges. To be able to work with sizes, the PositionedGraph is WPF-dependent and contains also the WPF user interface elements for graph nodes (PositionedGraphNodeControl) and edges (System.Windows.Shapes.Path). The PositionedGraph wraps an ObjectGraph and adds position and UI information.

#### Node layout

It the Analysis section, the Tree layout algorithm for calculating positions of nodes was proposed. The algorithm is implemented exactly as described, by selecting a tree subgraph using BFS and then recursively traversing the tree twice – first to calculate the areas needed for the subtrees and then arranging the subtrees next to each other. The implementation can be found in the TreeLayouter class.

##### Similarity to WPF’s “Measure-Arrange” layout algorithm – remove?

The two recursive passes over the tree are named Measure and Arrange in our algorithm. This fact that the two layout passes in WPF are named the same is not a coincidence – the layout algorithm in WPF and many other UI frameworks works on the same principle.

In WPF the user interface elements are organized into a tree called the Visual tree. When an UIElement is asked for its size (Measure() method) it asks its children for their desired sizes so that it can determine its own desired size. When an UIElement is told its new position (Arrange() method) it also repositions its children, knowing their sizes because Measure() is called before Arrange() for any element.

In WPF the users can define their own user interface elements and completely control the layout by subclassing FrameworkElement and overriding MeasureOverride() and ArrangeOverride() methods. This is also how existing UIElements are implemented. For example, StackPanel is a panel which stacks its children next to each other. This logic is implemented in the ArrangeOverride method.

#### Edge routing

After the node positions are calculated and fixed, the paths for graph edges are determined.

The problem: Given a set of positioned rectangles on a 2D plane and a set of directed edges between pairs of rectangles, find paths for the edges so that the paths avoid the rectangles and look *natural*.

Example of a solution (Graphviz): screeshot Graphviz

As discussed in the Analysis section, after researching available solutions it was decided that a custom solution would be implemented for the purposes of the Object graph visualizer. The implementation presented in this section is not WPF-dependent and can be reused as-is in other applications which is achieved by following a common practice of programming against interfaces.

##### Our algoritm

The first decision that has to be made when designing an edge routing algorithm is whether the edges will be routed globally or independently (one by one). The global approach means trying to minimize the total number of edge overlaps while making the individual edge paths look natural. The one-by-one approach means routing each edge independently from others, trying to make each edge path look natural.

Graphviz…

Like the edge routing algorithm in Graphviz (<http://www.graphviz.org:8080/Documentation.php> first), our algorithm processes edges one by one, treating each edge as separate input. The Graphviz paper also mentions a possibility of a global algorithm that would try to make edges avoid each other but does not provide any ideas for such algorithm. Ok?

When designing the algorithm, two important observations were made:

* The most natural path is a straight line and when there is a rectangle blocking the straight line, the path must be broken around some corners of the rectangle. There is no need to break paths in open space. Therefore, the interesting points in the plane which the paths should follow are the corners of the blocking rectangles.
* To make edge paths look natural to users, some sort of shortest path routing should be used.

The Graphviz paper confirmed our ideas – opravdu precten az po vymysleni, zminovat?.

The algorithm works in the following way: First a visibility graph is built, where vertices are the corners of all the rectangles, and edges connect pairs of vertices which can be connected by straight lines without intersecting any rectangles. Then, to find paths for edges, shortest path are being found in the visibility graph.

For each edge e in G:

Determine edge start and end point of edge e: take a straight line from the center of edge’s source rectangle to the center of edge’s target rectangle. Where this line intersects the source rectangle is the start point es. Analogically end point et.

Build the following graph Gv (visibility graph):

V = (every 4 corners every rectangle on input) + (for all e: es) + (for all e: et)

E = (pairs (u, v) from V where u is visible from v: straight line can be drawn from u to v without crossing body of any rectangle)

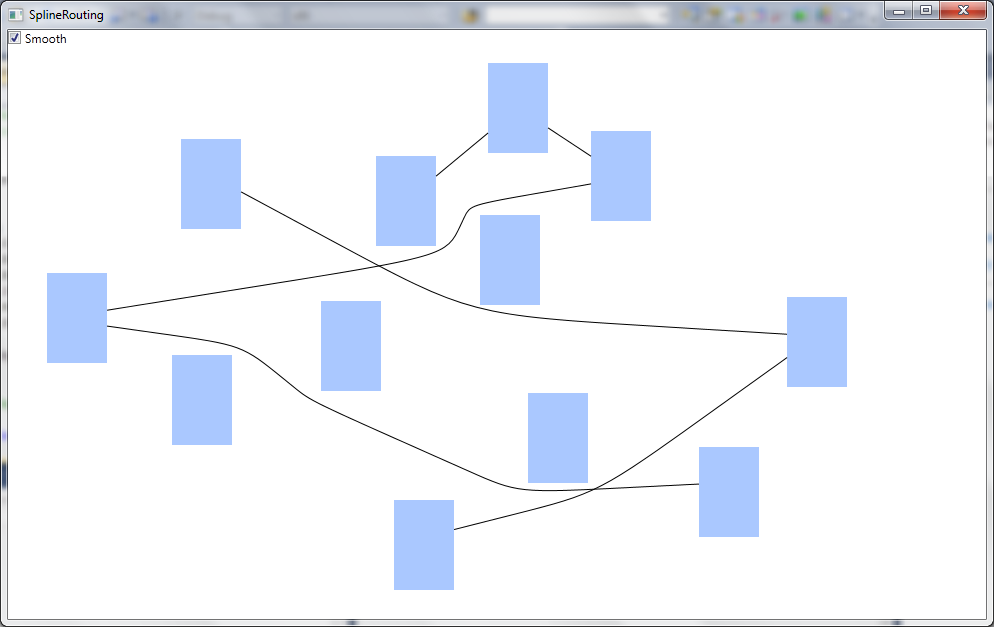
For each edge e in G:

In Gv find shortest path from es to et (using e.g. A\* or Dijkstra’s algorithm)

Smoothen the joins of obtained path by using Bezier curves

Note that the algorithm deals with the situation when boxes overlap.

Here is an example of a result:



The algorithm has time complexity of O(n3) where n is the number of boxes due to the construction of visibility graph: O(n2) vertex pairs are tested for visibility and each test needs O(n) line-rectangle intersections. It could be probably optimized but for our needs it is good enough.

Note that Graphviz also uses O(n3) algorithm.

Our implementation is completely reusable and can be found in the namespace Debugger.AddIn.Visualizers.Graph.SplineRouting. The reusability is achieved by defining simple interfaces and programming against them. Anything implementing these interfaces is then suitable input to the algorithm.

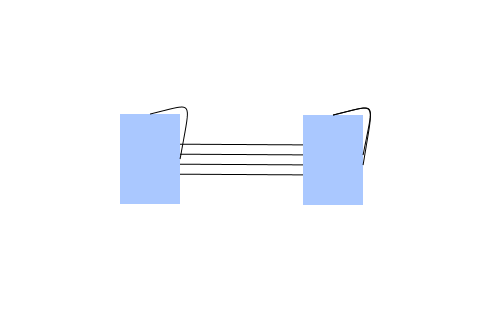


##### Edge overlaps

Routing edges independently can result in edge crossings and overlaps. To deal with possible edge overlaps, highlighting of edges under cursor is implemented in the Object graph visualizer.

Screenshot “the edge under the cursor is highlighted”

##### Multiple edges, self edges

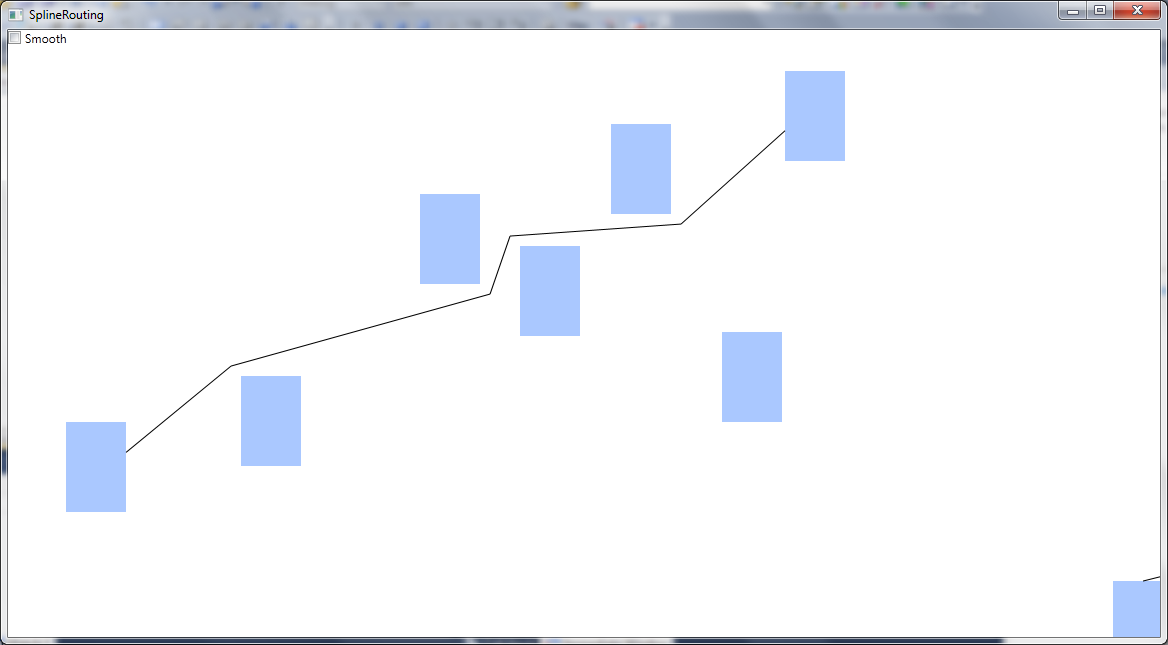
Our algorithm deals with the situation when there are multiple edges between one pair of boxes. This is solved by distributing the edge starting and ending points along the border of the boxes. Self-edges are solved in a similar way.

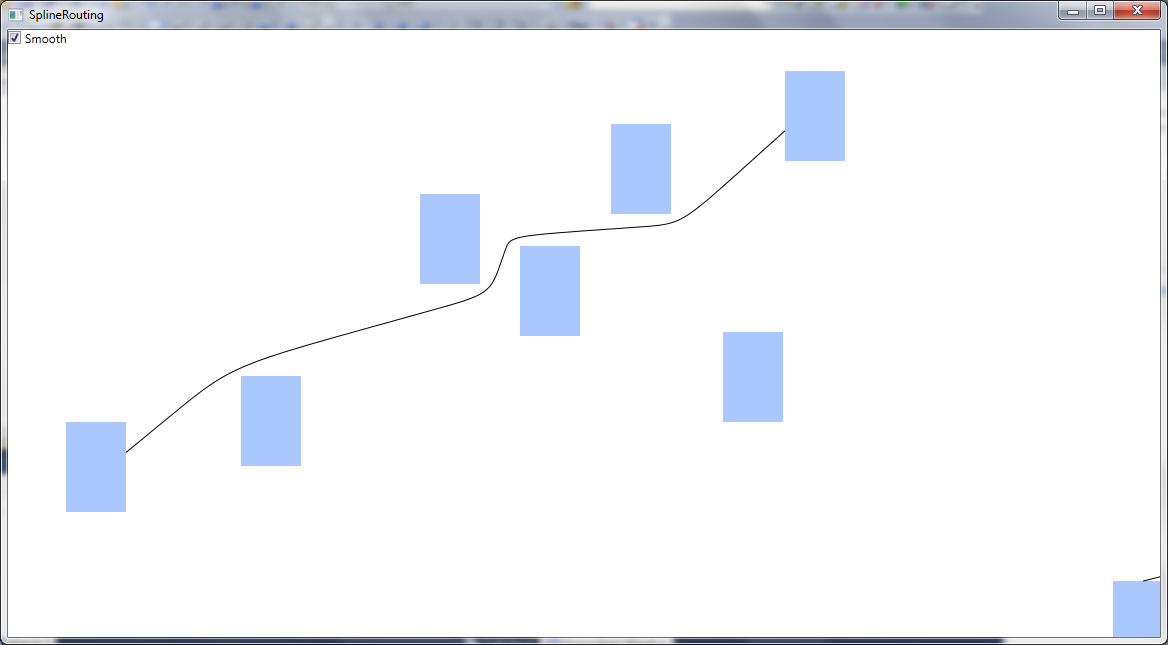
##### Explicitly determined start and end points

Some layout engines (including Graphviz) let users specify starting and ending points of edges. This feature could be useful in the Object graph visualizer because the edge outgoing from an object property could start directly next to the title of the property. We considered this and concluded that the layout would get problematic when the contents of nodes are scrolled – the edge point would have to move and the edge would have to be re-routed when scrolling. Therefore it was decided not to implement this feature for now.

##### Join smoothing

The last step of the algorithm – join smoothing – makes the result visually much more appealing:





The principle is the following: Given two consecutive line segments, replace the segments by a Bezier curve of order 3 extended by a straight line segments at each end:

Screenshot

The control points of the Bezier curve lie on the original lines. The distance of the control points from the original points determines the “smoothness” of the curve:

(Screenshot)

### Graph matching

Graph matching is used to produce graph transitions between two graph states. Graph matching is implemented as described in the Analysis section in the class GraphMatcher which accepts two ObjectGraphs and produces a GraphDiff object containing a list of pairs of matched nodes, a list of nodes which were added in the new graph, and a list of nodes which were removed from the old graph.

### Graph drawing and transitions

After the layout of ObjectGraph is calculated by TreeLayouter, producing a PositionedGraph, where nodes and edges are already represented by WPF elements, graph drawing is the final step which actually presents the PositionedGraph to users. Graph drawing is implemented in the GraphDrawer class, which positions graph nodes and edges on a WPF Canvas. GraphDrawer also produces the transitions by creating a set of WPF Animation objects (one animation per each node and edge) based on a GraphDiff. The animations transform an existing graph drawing to its new state.

While positioning the edges on the Canvas, GraphDrawer also adds tooltips to the edges, which appear when mouse cursor is hovered over the edges.

### The result

Here is a screenshot of the current version of the Object graph visualizer:

Big screenshot with code in the background

After the user does a step in the debugger – result.

All of the work described in this thesis is included in SharpDevelop 4.x. The best way to try the Object graph visualizer is to download SharpDevelop. link

## Collection Visualizer

Section 2.2 identified the conceptual difference between IList and IEnumerable collections and the need for obtaining collection items lazily. An important question of how to determine the columns for the Collection visualizer’s grid was also resolved. The Collection visualizer, implemented in CollectionVisualizerWindow, holds to these decisions. This section covers the data model of the visualizer, the implementation in WPF and explains how not only rows, but also columns of the grid are evaluated lazily for best possible performance.

### Lazy loading items when scrolling

Following our common approach to collections, any collection which is not an IList is converted to a List prior to being visualized. The implementation uses a WPF ListView and exploits the way in which ListView accesses items from its ItemsSource. When the ItemsSource is an IList, the ListView accesses the items which are needed to be rendered using the IList’s indexer.

Our implementation supplies a special collection, called VirtualizingCollection, as the ListView.ItemsSource. This collection is a wrapper around some data source (in our case the debuggee collection) and when asked for an item at index *i* it queries its underlying data source for item *i*, returns it and caches it. This principle is often referred to as *data virtualization*.



The top half of the class diagram is a generic data virtualization implementation. The bottom half is specific to debugging. The items returned by the indexer of ListValuesProvider are instances of ObjectValue – a representation of a collection item specific to the Collection visualizer. ObjectValue contains the index of the item in the collection and a map of values of item’s properties.

The map is used to provide indexing by property name, which is used by the data binding of dynamically created ListView columns. The following listing shows how columns are created dynamically and prepared to be bound to ObjectValues.

**foreach** (var member **in** itemTypeMembers)    {  
                var memberColumn = **new** **GridViewColumn**();  
                memberColumn.Header = member.Name;  
                // "{Binding Path=[Name].Value}"  
                memberColumn.DisplayMemberBinding = **new** **Binding**("[" + member.Name + "].Value");  
                gridView.Columns.**Add**(memberColumn);  
}

#### Note on generic data virtualization

Note that in our case, the only way to get a set of items from the debugger is to query items one by one. However, there are scenarios where querying a range of items at once is faster than obtaining items one by one (for example relational databases). In such scenario it is reasonable to implement paging mechanism in the concrete value provider so that when the provider is asked for an item at position *i* it queries and caches a number of items around index *i* because it is very likely that these items will be needed soon. –ok?

### Expanding items in the grid

Because the properties of each collection item, shown in the individual grid cells, can be complex objects themselves, we implemented a way to explore their contents - each item of the collection has an expand button which opens a standard debugger tooltip for the item.

Screenshot

We implemented the expanding in the following way: Each item is represented by an ObjectValue which holds its index. To expand the tooltip, we pass an expression representing the item (like “list[12]”) to a debugger tooltip and open it at a right position.

### Generic vs. non-generic collections

There is an important question when designing the collection visualizer – when given a collection, what should be the columns of the grid? We already discussed this in the Analysis section. We decided that the grid columns represent the properties of the single generic parameter of the collection. That means when we get IEnumerable<Person> we make one column for each public property of the class Person and its base classes.

When the collection contains subclasses of the generic parameter type, their properties are not shown. Showing properties of subclasses would mean leaving the cells empty for some rows, since they would miss the properties, and adding columns dynamically on scrolling. We are not doing this.

Mockup of how it would look (in Excel)

Using the generic parameter also means that we do not support non-generic collections.

Building the columns is implemented in GridVisualizerWindow.

### Lazy loading columns (object properties)

In the collection visualizer, we are evaluating rows on-demand, as the user scrolls down (this was described in the section Lazy loading items when scrolling link). But we are also loading the individual cells lazily - the user can select which columns to show and which to hide. When a column is hidden, it is not being evaluated. When the user decides to show the column later, the values in the column are only evaluated for the few items which are currently in view. In other words, the visualizer is as lazy as it can be.

The implementation exploits the way the WPF ListView evaluates databinding expressions. We bind ObjectValue[propertyName] to each column, and when a column is hidden, we remove it, so the ListView stops evaluating it. When we add the column back, the ListView only asks for the values which are currently in view. The laziness is implemented in ObjectValue and the databinding can be seen in where.

### The result

Screenshot of collection visualizer

The screenshot shows the current version of the collection visualizer. Each row represents one item, each column represents one property. This is very similar to how relational data are typically presented. Indeed, collection visualizer can also be used to display collection of objects loaded from a database. In such case the user sees the data in the same way they are used to.

Show also IQueryable, ObservableCollection, IParallelEnumerable.

## Debugger tooltips

Unlike with the two previous visualizers, the data model for the tooltips was already there in SharpDevelop. It didn’t support large collections so we had to add this to the data model.

The main part of work on the debugger tooltips was to implement the user interface and integrate it in into SharpDevelop’s code editor. We wanted the tooltips to work for C# and VB.

### The result

# Conclusion and future work

Great idea – integrate collection visualizer into tooltips. When a collection is expanded in the tooltip, clicking a small arrow adds columns.

In tooltip button to include properties from all base classes, so that user does not have to search. Or add type-to-search feature.

Draw a forest – all the local variables for example, with markers to show which node is which variable.

Special case for Dictionaries.

Plot visualizer (for someone interested).



# References

[36] SYBASE.COM. www.sybase.com/products/databaseservers/sybaseiq. Product page.

[37] Zhao, B. Y., KUBIATOWICZ, J., AND JOSEPH, A. D.

*Tapestry: An infrastructure for fault-tolerant wide-area*

*location and routing.* url

# Appendices

## User documentation

## Content of DVD