Distributed Doodling

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Abstract

Communications for the business and academic world is increasingly taking to the digital highways of the internet. As yet though, there is no easy way for a group of peers to collaborate together on a design project involving diagrams being analysed and reworked. This project addresses that issue in attempting to create a distributed system that allows a group of people to connect over the internet and collaborate on a drawing.

The construction of the Tabula application was the result of the Distributed Doodling project. The application aims to provide the desired chat and drawing solution for collaborations by multiple users. To aid the construction of the application, the Qt framework was chosen to support the GUI development while RakNet was found to provide the desired network functionality. Qt provides many useful widgets that greatly simplified development and the signals and slots system creates an easy to use method for connection possible user actions (pressing a button for example) to a function. RakNet provides permits for the layering of some TCP like features over a UDP connection, greatly reducing the overheads that would have been associated with using TCP. Overall the architecture has been designed to be highly extensible in anticipation of future functionality being added.

Custom 'Events' have been designed to represent actions of the user; this may include drawing an object or sending a text chat message. To keep a record of these `Event` objects a logging system has been developed which uses a unique logical timestamp system to allow every `Event` to be identified and ordered. This uses vectors of logical timestamps to identify each system and avoid local clock synchronisation issues. A user action will cause the logical clock in that users system to tick with other users system clocks being updated when they receive the `Event`. So that sessions can be saved and restored, XML is used to save the history of the session to hard disk.

Live drawing was an interesting addition to the application, allowing users to see other members of the conversation drawing in real time. This also allowed us to take full advantage of the optional TCP like features on the UDP connection that was being used. Temporary events allow users to see objects being manipulated remotely however if a few of these are lost of arrive out of order, it is not important. Therefore, for these temporary events we were able to use a standard UDP connection, again lowering the necessary bandwidth. A peer to peer network system is built ontop of our enhanced UDP connection, creating a robust connection between all peers with the ability to reconnect peers if an intermediate system fails.

The application provides a solution that has not previously existed. Testing on the log system shows that it is able to operate faster than a high speed network can deliver events from multiple users. The application has been a success as far as reaching the key, and many of the advanced requirements are concerned. There remain some advanced requirements that could be implemented and there are highly complex features that could be added that were always considered beyond the goals of the project. The GUI may be considered a 'contractual GUI' in that it looks very simple and minimal and possibly work by a professional designer could help it look more appealing.

Contents

1 Introduction

1.1 Motivation

A picture is worth a thousand words. Often quick sketches can be used to explain a concept much more concisely than words ever could. However, there has always been a problem with drawing and sending such pictures easily and efficiently over the Internet. As the Internet is quickly replacing conventional meetings and provides many benefits, such as removing the costs of travel and time, it is becoming ever more important for a functional distributed drawing solution.

Our project, Tabula, aims to fill this gap that commercial software has left in the online communication and collaboration fields. There are many existing systems that provide either online messaging or drawing features, including Windows Live Messenger or iScribble, however these are primarily instant messaging systems with a drawing application added for fun. We aim to provide an application which focuses on the problem of many users attempting to collaborate in areas where diagrams are the primary method of communicating ideas and constructs.

We have approached this problem in collaboration with our project supervisor Professor S. Drossopoulou, our initial target user, who wishes to use this application in her research field.

1.2 Requirements

We chose a set of requirements which we feel will produce a highly productive and feature rich initial release of Tabula. These requirements were reached from interviews with our project supervisor, comparison with existing projects (Section 1.4) and features which the group believed would provide a more immersive tool.

1.2.1 Key Requirements

Collaborative Drawing: The ability for multiple users to draw on the same canvas at the same time.

Distributed: Operates over a network without a dedicated server machine.

Text Chat: An instant messenger client allowing for text based communication between whiteboard contributors.

Freeform drawing: The ability to draw freely on the canvas with a pen-style tool.

Object Repositioning: Allow users to reposition elements once they have been placed on the canvas.

Vector Resizing: Freeform object resizing whilst maintaining precision, unlike raster graphics.

Text Labels: Addition of text to the canvas

These basic requirements are what the final solution requires to be a productive tool. The most complicated of these requirements will be the implementation of the distributed elements of the solution.

1.2.2 Advanced Requirements

Logging: Provides functionality for recording a session, allowing for playback or undo/redo actions.

Version control: Allows users to go back through the log and branch the diagram.

Joining of a session after it has started: Update anyone that joins with the entire session log and current version of the whiteboard.

Save and resume sessions: The ability to stop and continue drawing sessions at a later date with full history and versioning.

Click and drag-to-size polygon palette: A palette of common polygons that can be selected, placed and resized in a single action.

Permissions on drawing: Set sections of the canvas to be non-editable by others.

Export diagram as image: Allow the user to send a fixed version of the whiteboard to any person in an image format.

Audio chat: Provides a more immersive experience than text chat, to be integrated into our logging system.

Tabbed canvases: Multiple canvases within a single whiteboard session for separation of drawings and ideas.

Layered canvas: Set the order in which objects are to be drawn onto the canvas.

Auto-correction of lines: Simplifies freeform drawing by correcting basic input errors.

Shape Recognition: Detect and replace objects that appear close to triangles, square, circles and basic shapes as these are hard to draw accurately with any input device.

These advanced requirements will increase the appeal of Tabula to a wider audience of users by increasing core functionality, improving accessibility to novice users and extending the areas of use for the application from the original specification.

1.3 Use Case Diagram

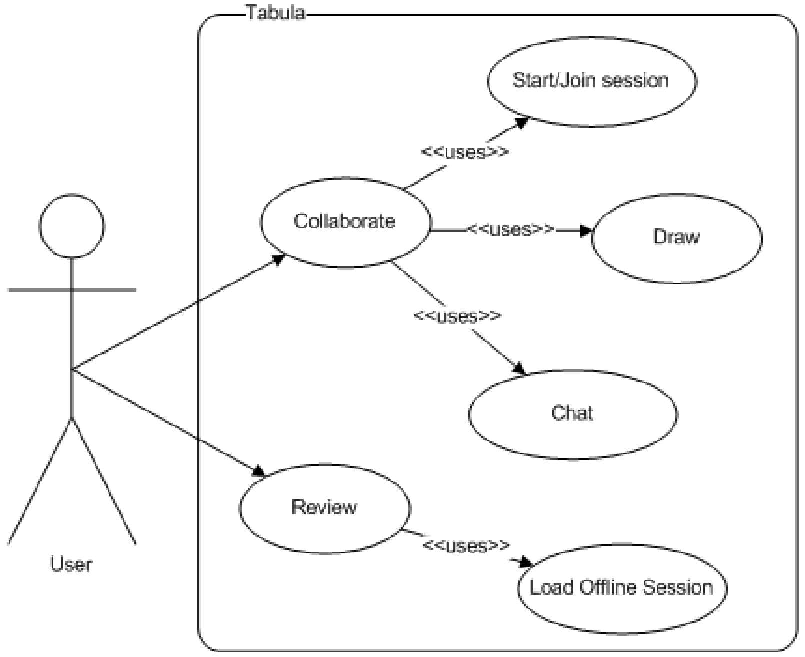


Figure 1: Use case diagram for a Distributed Doodling based application modeled in UML

The main functionality and purpose of Tabula should be to enable collaboration, reviewing and archiving of diagrams as part of a greater research goal. This results in the requirements of having a session and sending / receiving messages and drawn objects; the ability to resume sessions at a later date and ultimately to archive the result of a collaboration in a more standard format such as an image file.

1.4 Similar Solutions

There are a number of solutions available that provide parts of our desired solution. We compare these applications against our requirements in Table 1. These solutions are typically applications developed for Tablet PCs which have been extended to normal PC usage by replacing the pen with a mouse cursor. Freeform drawing with a mouse is a very unnatural and imprecise method of input resulting in poorly formed shapes.

1.4.1 Windows Live Messenger

The closest standalone application available is the widely used[29] Windows Live Messenger[27] which has the ability to draw simple pictures and send them within a group conversation. However there are a number of issues with this solution.

Messenger is historically a chat based Instant Messaging system[30] to which the ability to speak, draw, play games and such have been added. Thus the main

Feature	Live Messenger	Journal	iScribble	Tabula
Collaborative Drawing	✗	✗	✓	✓
Distributed	✓	✗	✓	✓
Text Chat	✓	✗	✓	✓
Freeform Drawing	✓	✓	✓	✓
Object Repositioning	✗	✓	✗	✓
Vector Resizing	✗	✓	✗	✓
Text Labels	✗	✓	✗	✓
Logging	✓	Undo/Redo	✗	✓
Version Control	✗	✗	✗	✓
Joining of Existing Session	No History	N/A	✓	✓
Save & Restore	✗	✓	✗	✓
Polygon Palette	✗	✗	✗	✓
Permissions on Drawing	✗	✗	✗	✓
Export Diagram as Image	✗	✓	✗	✓
Audio Chat	✓	✗	✗	✗
Tabbed Canvases	✗	Multi-instance	Multi-instance	Multi-instance
Layered Canvas	✗	✗	✓	✓
Auto-correction of Lines	✗	✗	✗	✗
Shape Recognition	✗	✗	✗	✗
Continuous Editing	✗	✓	✓	✓
Live Drawing	✗	N/A	✓	✓

Table 1: A comparison of existing software, each of which provide part of our desired functionality, against the final Tabula release.

focus of Messenger is text based conversation and this results in poor drawing integration. As can be seen in Figure 2, the default proportions between text and drawing are biased towards text conversation; drawing can only be accessed from within a special tab in the chat entry box, thus a user cannot draw and chat at the same time. The only input method is freeform drawing using a Tablet PC pen or mouse pointer - shapes cannot be selected from a palette.

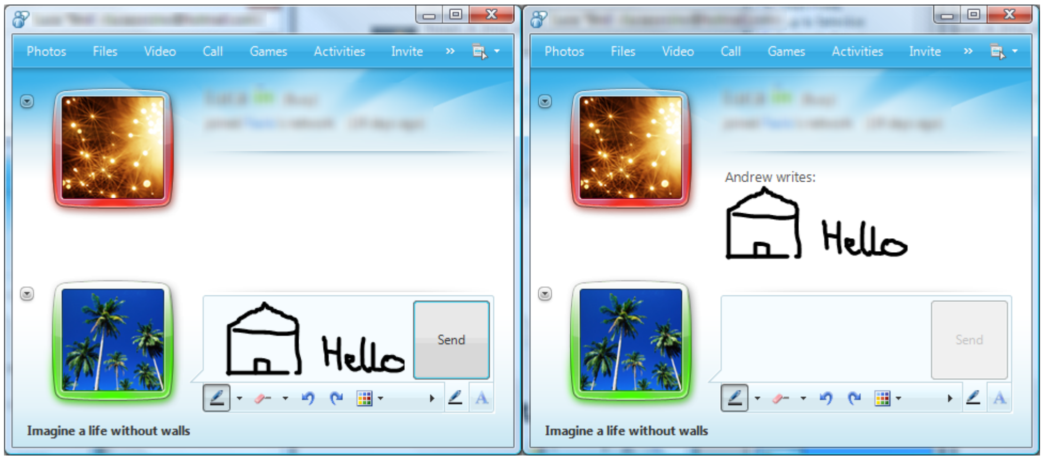


Figure 2: Windows Live Messenger v14.0 showing small drawing space and inability to re-edit sent images. Note standard freeform drawing errors: jagged lines, points not meeting and lack of ability to send text whilst drawing. Right graphics shows drawing once sent, it cannot be edited.

Most importantly, the drawing feature does not include the ability for another user to modify the drawing and return it. The concept of multiple users modifying the same drawing is one of the fundamental goals of the project and therefore the lack of this ability in Windows Live Messenger severely limits its use as a viable option.

1.4.2 Windows Journal

Windows Journal[35] is a notepad tool developed for Tablet PCs released with Windows XP Tablet PC Edition. It provides the user with a canvas, typically with ruled or grid lines, upon which the user is able to scribble notes and diagrams. This can then be saved to file or exported as an image. If saved in the Journal format, it can be re-opened and editing can continue.

Windows Journal provides freeform drawing and the ability to select and resize objects once drawn. However, Windows Journal is an offline application with no messaging facilities which is also hampered by Microsoft's support for the product. As it has been developed for a Tablet PC, the writer application is only available on Windows XP Tablet PC Edition and Windows Vista; older versions of Windows (2000, XP and Server 2003) only have a reader application available[26].

Windows Journal does offer several advanced features to Tablet PC users, these include handwriting recognition and the ability to dynamically insert vertical space into a document. We believe that handwriting recognition would be

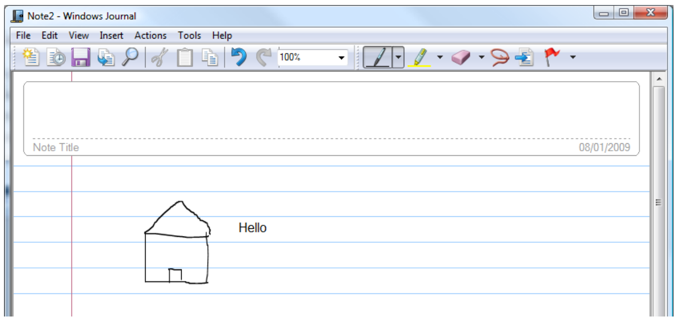


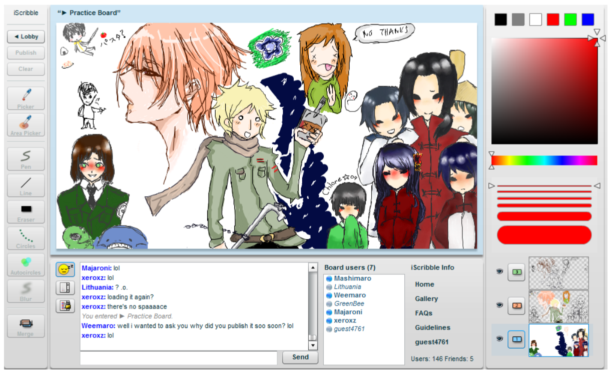
Figure 3: Windows Journal v6.0 showing the ability to draw and type on the same canvas. Note the lack of pre-defined shapes for mouse entry.

of benefit to many users, however we feel this to be beyond of the scope of this project and recommend it as a possible extension.

1.4.3 iScribble

iScribble[14] is the closest application to the problem that the team has found. It is a browser based application running on Adobe Flash and therefore is cross platform and only requires installation of the Flash Player, a standard browser plugin with a 99.0% install base[4].

iScribble provides an interface consisting of a canvas with simple tools for lines and circles, a standard text chat interface and a layer panel. It also features a highly customisable pen tool with adjustable thickness and full colour palette. Drawing sessions take place in “Rooms” which can be set to public or private upon creation.



Majaroni: lol
xeroxz: lol
Lithuania: ? .o.
xeroxz: loading it again?
xeroxz: there's no spaaaace
You entered ▶ Practice Board.
Weemaro: well i wanted to ask you why did you publish it soo soon? lol
xeroxz: lol

Figure 4: iScribble.net public room showing a user friendly interface and clearly defined options.

The main weaknesses of iScribble lie in the inability to save and review the session at a later point whilst also lacking a way to export the image from the application. There is no user accessible log of the drawing construction, however the application itself runs on a logging system. This can be seen when entering a room as the various layers and objects are drawn onto the canvas. Due to this non accessible log iScribble does not support modification once a draw action has occurred; hence it features no selection, delete, move or undo tools.

iScribble relies heavily on users having a graphics tablet or Tablet PC as the only built in shape is a straight line - all other shapes must be drawn freehand. Users are also not able to put text labels on drawings. If any labels are required they may be drawn using the free-form drawing functionality of iScribble, in a similar way to Windows Live Messenger.

Finally, unlike the other similar solutions reviewed, iScribble is an Internet application hosted on a 3^{rd} party. This results in no guarantee of security or privacy when using iScribble. There is also a limitation on the types of drawings that can be created on iScribble as its main intention is to create artistic imagery, this is enforced via a terms of use agreement and an account banning system[13].

1.4.4 Conclusions

The project is looking to create a combination of these applications for the standard keyboard and mouse input system. Ideally there should be similar chat functionality to Windows Live Messenger combined with the natural freedom to draw provided by Windows Journal and iScribble. The failings of not being able to draw standard shapes is an area that will specifically be covered by our application.

2 Tools and Frameworks Used

2.1 Qt

Qt is a cross-platform application framework[34] which is widely used in both commercial applications and open source projects. It provides a comprehensive modular framework for developing **Graphical User Interface (GUI)** applications. Many well known applications have been developed using Qt including Google Earth, Skype and Adobe Photoshop Album[33]. Over the last decade it has cemented its position as the diamond standard C++ framework for cross-platform software development[31].

2.1.1 Widgets

Qt provides a large range of standard **widgets** that we used to create the GUI. These widgets include everything from simple push buttons to graphical canvases and sliders for fine grained selection. Layout managers were used to arrange the widgets and also perform automatic positioning and resizing depending on the contents or window size. These widgets support the **Model View Controller Pattern (MVC)**, a pattern we adopted frequently throughout the project which is further discussed in Section 3.1.1

2.1.2 Signals & Slots

One of the most important features of Qt is the way it handles input from the GUI. When a widget is used it emits a signal, for example a button may emit a 'clicked' signal. The developer can then choose to connect a signal with some action by creating the appropriate method, called a 'slot', then connecting the signal to the slot by calling Qt's `connect()` function.

The connections between signals and slots are very flexible; the signals can be dynamically remapped to different slots at any point during execution. They are implemented in standard C++ using the C++ preprocessor and the **Meta Object Compiler (MOC)** that is included with Qt. MOC reads the header files and automatically generates the necessary code to support the signals and slots mechanism. Qt gives you the choice of using a provided compiler (QMake) to compile all code and automatically run MOC where required. However we manually ran the MOC tool on our header files since we were using the VC++ third party compiler.

Connections can also be made between objects in different **threads**. Although not directly used within our project we believe this would be a useful feature for future extensibility. For example, this could be used in conjunction with processor intensive extensions such as handwriting recognition which needs to process data as it's created without reducing the application's response time.

2.1.3 GUI Support

Often in modern GUIs there will be a number of ways to perform the same function. For example, we have a 'save' menu option and key combination

(Ctrl + S) which perform the same action. If we later decide to implement a toolbar button this would be trivial to hook into the same handler. Qt supports the ability to have multiple triggers for the same function by way of the `QAction` class. This ensures that wherever an action is invoked from, the states of the different elements stay in sync. Therefore, if an action is disabled both its menu and toolbar selectors will be disabled.

All the standard features of a modern GUI are supported in Qt. The `QMainWindow` class provides the framework for a normal application window. The `QMenuBar` provided the standard style menu bar which we populated with our own choice of commands.

2.1.4 Issues and Quirks

In providing the modularity and flexibility of a large number of standardised widgets, Qt poses some unexpected issues. Qt typically has widgets consisting of either a default implementation which can be inherited and methods overridden or an abstract class with pure virtual methods which must be implemented. In particular, the `QGraphics` system provides us with several basic shapes, primarily `QEllipseItem`, `QRectItem`, `QLine`, `QPath`. These classes are part of the Qt library and are totally closed for modification. Modifying these objects directly in order to extend them would be a non trivial task as it would have a ripple effect through classes we don't use and would make the task of upgrading the library with new releases difficult.

Instead we extended these classes to add functionality to them, then we casted down from `QGrahpicItem` type to our extended type since it is not possible to produce what we refer to as the 'Diamond' pattern as shown in Figure 5. This is because we cannot use virtual multiple inheritance since this would also require access to the Qt classes, we deal with the solution to this in Section 3.4.6 but suffice to say that the class responsible for casting is encapsulated and isolated as much as possible.

It should be noted throughout the rest of this report that all classes prefixed with a Q are Qt classes implemented for us which we use directly, extend or override, but cannot modify. We highlight these as shown in Figure 6(a). In addition, class diagrams will contain classes displaying only their name, these are to indicate a link to other diagrams where they are shown in greater detail, these are identified as per Figure 6(b)

2.1.5 Justification

Qt provides both Java and C++ implementations of its framework. Therefore it presented itself as a good choice in the very early stages of the design process as it was not dependent on which of these two languages was eventually chosen. It was also very important that the framework was provided as open source. There should not be any license issues with using the framework regardless of how widely used an application becomes.

Although Qt does provide a certain amount of networking functionality, in terms of the project requirements this was the main weakness of the library.

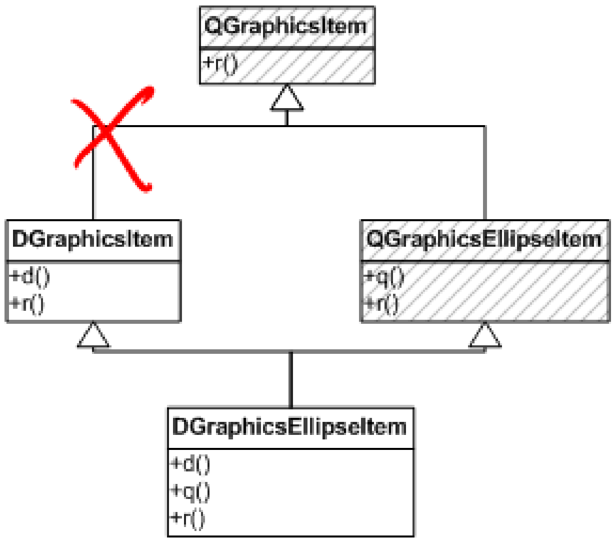
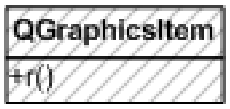


Figure 5: Lines indicate inheritance, note the line from `DGraphicItem` to `QGraphicItem` doesn't exist in our implementation.



(a) Qt classes represented via hatching. These are uneditable.

DGraphicsItem

(b) Borderline classes. These are detailed in other class diagrams.

Figure 6: Examples of custom UML representations used within our class diagrams.

Instead we sought out an alternative networking library, RakNet.

There are no real alternatives to the entire Qt package as it provides a fully featured framework and a GUI. Due to the use of MVC throughout the Qt libraries it makes using a library and pushing results through to the user a fairly streamlined and standard process. If we were to use a combination of a GUI toolkit and distinct libraries far more overhead would be required to convert data structures from libraries so that they could be supported by the GUI.

We did find alternatives to using Qt for GUIs, these included GTK+, wxWidgets and FLTK. GTK+ is a cross-platform toolkit which supports C++, however the Windows performance of GTK+ is rather poor and highly laggy. Both wxWidgets and FLTK are poorly implemented and produce rather poor and dated GUIs. Ultimately the superior graphical functionality (as can be seen by the ability to produce Google Earth), programmer experience and the framework and GUI integration provided by Qt significantly reduced development time.

2.2 RakNet

RakNet is a mature and well documented **User Datagram Protocol (UDP)** based networking library written in C++ which has been designed primarily to "add response time-critical[sic] network capabilities"[16] to applications. RakNet consists of a core library with a highly modular plugin system, providing a streamlined codebase.

During the design stage our networking requirements consisted of performance, flexibility and expansibility more than feature set. RakNet proved to be a suitable library which provided the ability to easily integrate new features in the future, whilst meeting and exceeding our performance requirements.

2.2.1 TCP vs UDP

Our project uses UDP based networking rather than **Transmission Control Protocol (TCP)** based networking. We made this decision based on our requirements for the network to be high performance and the fact that TCP networking has a higher operational overhead. This overhead comes from several features that TCP provides such as guaranteed delivery, **packet** ordering and congestion management. Out of these features, we only require guaranteed delivery and packet ordering in certain areas, both of which can be implemented on top of UDP as optional features. This gives us flexibility by having the performance of UDP and the reliability of TCP available in the same connection.

2.2.2 Reliability and Ordering

As stated in the Section 2.2.1, we required a library which implements a UDP based network with some features of TCP. RakNet's communication layer provides just that.[18]

RakNet's implementation of message ordering, the ability to cache out of sequence messages until they can be processed in the correct order, allows us to have multiple ordered streams. Different streams are different sequences, so unrelated packets won't be held up waiting for each other to be processed. This allows our chat, drawing and session packets to all be processed and ordered independently such that, for example, lost packets and delays in the chat queue do not slow up the drawing or authentication mechanisms. We felt that this was an important benefit as drawing is the main aim of our project and we do not want it to be slowed by our extended functionality.

2.2.3 BitStreams

To send data across a network it must be serialised, endian swapped (where required) and ideally compressed. This can be done manually using custom functions and data structures, or automatically by the network library via provided utility objects.

Searching for such a facility brought us to the attention of RakNet's `BitStream` class. This class converts and compresses passed objects into a stream of bits ready for sending across the network.

RakNet's `BitStream` class noticeably reduced development time, as we were able to pass any combination of primitive types or character arrays, greatly easing the serialisation of objects.

2.2.4 VOIP Support

One of our advanced feature requirements was VOIP**Voice Over Internet Protocol (VOIP)** support, which would have needed to interface with the network plugin, possibly using a separate connection to the rest of our data. It was important that adding such a feature wouldn't threaten the stability or performance of the existing network code, so our chosen network library had to be modular enough to support extensions without requiring any changes to the core functionality. RakNet features a simple to use VOIP plugin which supports this requirement whilst also featuring built in compression for voice chat.

2.2.5 Justification

An important part of selecting a library to provide our network layer was making sure that what we picked would 'Just Work'. Reliability was key, because any significant time lost to networking bugs could have jeopardised the project's success.

Finding a library which supported all our initial design requirements, allowed a lot of future expansibility and had a proven track record of success brought us to RakNet. RakNet is UDP based with full support for sending reliable, stream ordered packets, and supports many platforms including Windows, Linux, Mac OSX, PS3, and XBox[19].

It has a plugin system for adding new network features without changing the core functionality - important for both extensibility and reliability. It also supports the serialisation and compression utilities that we desired in the form of BitStreams, which would reduce the development cost of our application.

On top of these points, RakNet is used by large development studios such as Sony Online Entertainment[15] and Codemasters[15], who have given it glowing reviews. This record of being used in performance and reliability critical products gave us great confidence that we would have the same experience.

Alternatives to RakNet that we investigated included the Torque Network Library (OpenTNL)[11] and the C++ Sockets Library.[12] OpenTNL provides most of the same features that RakNet does, so it could have been an ideal alternative. However it is currently unmaintained and research found evidence of some incompatibility with newer compilers[25]. This greatly increases the risk of problems during development which would threaten our progress, as we would have had to fix these issues ourselves. The C++ Sockets Library is a C++ wrapper around the Berkeley sockets C API. It is well written and cross platform, with a good user testimonial.[36] Unfortunately the implementation is lacking in key features that we required, such as optional TCP features upon UDP. Having to implement that ourselves would have greatly increased development time.

3 Architecture & Design

In this section we aim to explain the overall system architecture and design. This requires giving an overview of our various subsystems, however these will be explained in greater detail later in the report.

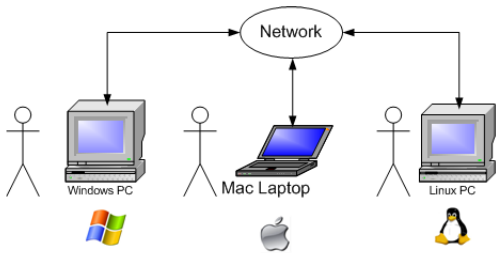


Figure 7: Diagram representing the heterogeneous environments of PC, Laptop and various OS's our project will operate over.

Figure 7 describes the problem from the user interaction point of view. Multiple users on different workstations using different operating systems collaborate with each other over a network of some sort.

3.1 System Overview

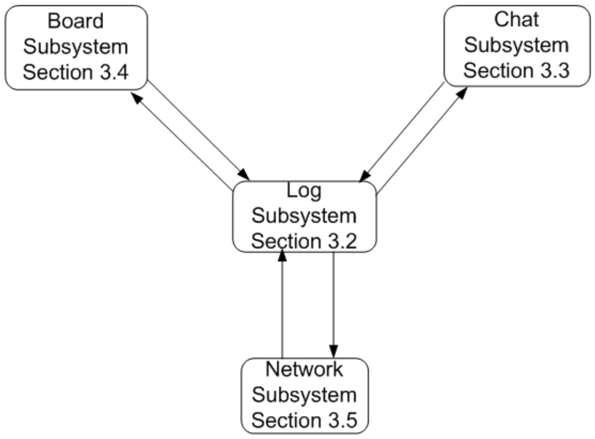

Board Subsystem Section 3.4
Chat Subsystem Section 3.3
Log Subsystem Section 3.2
Network Subsystem Section 3.5

Figure 8: A high level representation of how the 4 main subsystems interact.

We show in Figure 8 how our four main subsystems interact. The `Board` subsystem allows graphical collaboration between participants, the `Chat` subsystem allows verbal collaboration between participants, the `Log` maintains a record of every collaborative action taken by any user, providing us with a back end for version control and the `Network` subsystem facilitates the sending and receiving of data on behalf of each instance of the application.

3.1.1 Model View Controller

Each subsystem contains a controller which indirectly interacts with the controllers of other systems. This extra layer of indirection is implemented as

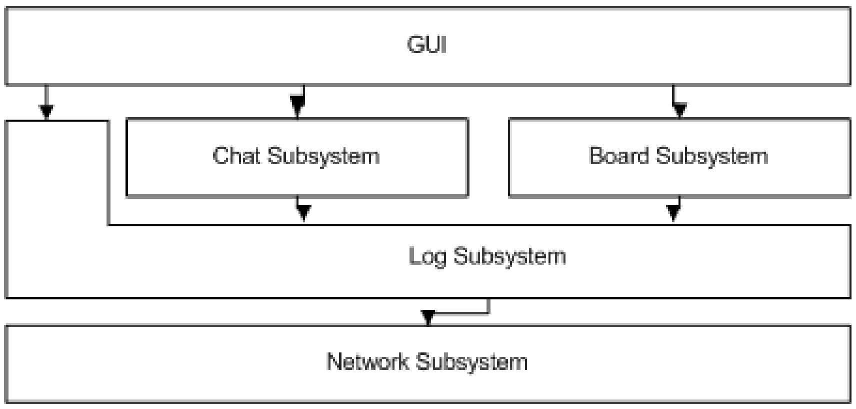


Figure 9: A diagram representing how the different levels of our application are able to communicate with each other.

a callback method in each controller and ensures lower coupling between the different subsystems.

Qt's graphical widgets are designed with the Model View Controller pattern in mind and, because most areas of internal representation need some sort of display, the patterns' appearance is quite extensive in our design. It appears in the `Board`, `Chat` and `Log` system.

3.2 The Log Subsystem

The log is intended to be a record of every event that happens in the system such that if given a log one can reconstruct the state of both the board and chat system from the start to any point up until the end of the log. Such a system aims to provide the foundation for being able to mimic version control systems such as SVN. The `Log` class itself is a container for an ordered n-ary tree of `Event` objects referenced in their abstract form coupled with the appropriate access methods. The event data of permanant objects recorded by the log should be immutable and idempotent. This is to ensure consistency as users extending our project may misuse the log, resulting in undefined behavior.

We have two distinct situations where we need to represent the log. Firstly we have the live log which is to be kept in memory when the application is running. This representation requires the ability to quickly navigate and modify the log whilst being compact such that we do not require large amounts of system memory. Secondly we require an offline representation of the log to be kept on disk for the purposes of saving and resuming sessions. This log requires the ability to be transportable and remain valid for all versions of our application (and any underlying frameworks that we use).

3.2.1 The Live Log

Let us consider the notion of an event object to describe what has happened. An event is an abstract class which can be implemented by any of the following concrete classes:

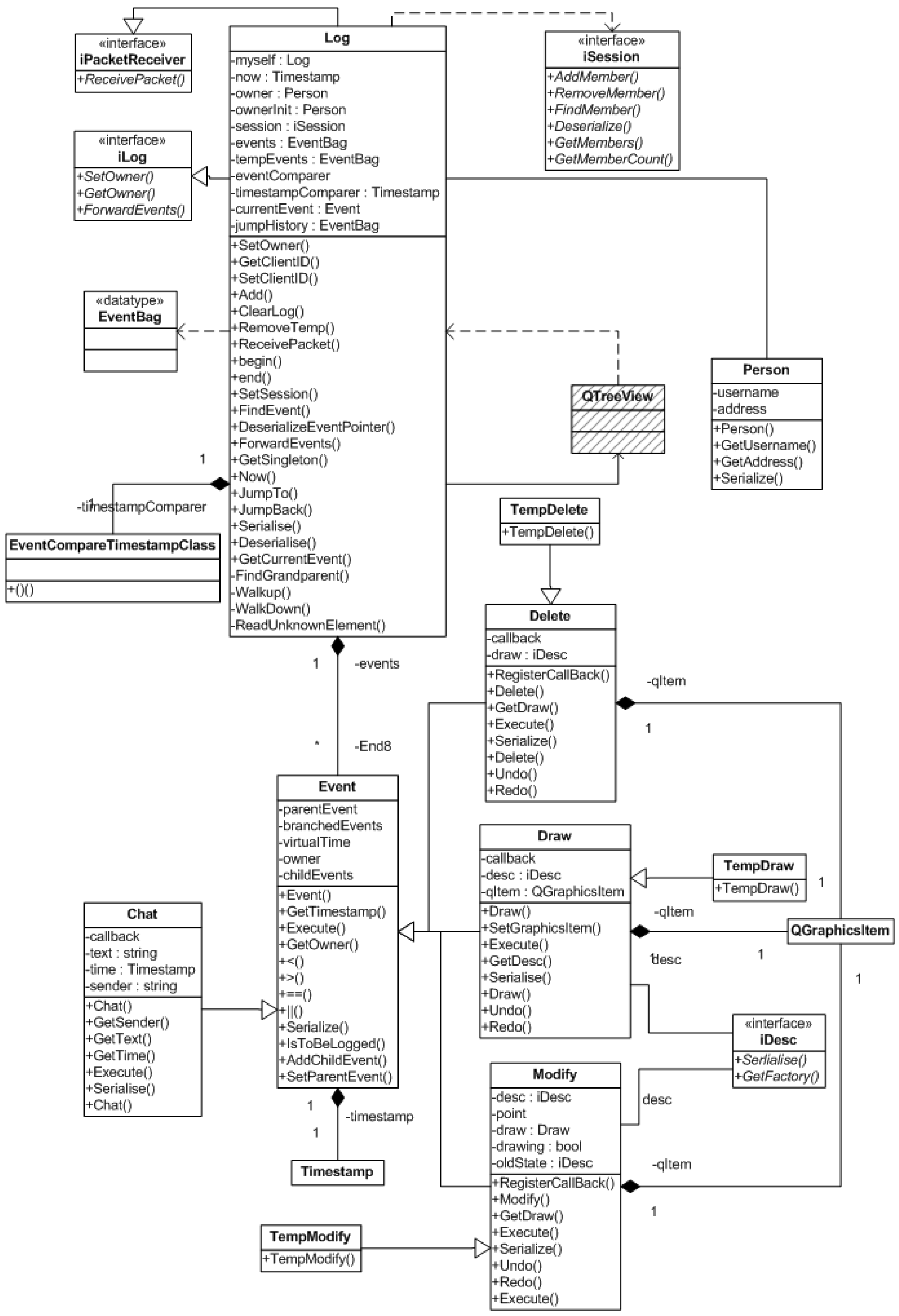


Figure 10: The log subsystem's class diagram.

Draw object Contains the necessary information to instantiate any graphical widget.

Modify object Contains the necessary information to modify any graphical widget.

Delete object Contains the necessary information to delete any graphical widget.

Chat object Contains a string payload describing the contents of a message, along with other information (sender, time created, etc) for the chat system.

Both `Draw` and `Modify` objects need to be able to describe the objects they apply to. Ultimately, we chose implement the bridge pattern and have a pointer to a descriptor (Desc) object which describes the dimensions and locations of the object. The upside of this is increased extensibility, in order to add an operation we can simply add a concrete `Event` which performs that operation. Similarly, in order to add a custom shape we simple add a single concrete descriptor for the new shape.

In addition, by having the abstract `Event` class coupled with a well defined interface, the log does not need to know the concrete type when recording an event and can still carry out general operations upon it. These concrete classes each implement their own methods and callback the relevant controllers from each subsystem by overriding the superclass method through polymorphism, this is done for `Event execute()` and other similar methods. Along with these benefits we are also able to reduce network traffic. By sending only the parameters required to create an `Event` through our use of descriptors we reduce the amount of data required compared to sending the instantiated object itself.

Due to this method, `Event` objects now contain pointers to a `Descriptor` object. This requires special handling when serialising for network transmission. This is non-trivial and was one of the biggest challenges we faced. We explain this in detail in Section 5.5.

Alternative Methods Explored: To arrive at the descriptor approach we looked at several other methods of representing events which did not require the use of pointers in an attempt to avoid the serialisation challenge. Initially we hoped to describe the event via a single class which describes the event by name, through concatenation of the action and the shape it is applied to (e.g. drawRectangle), rather than by composition. Essentially if there are p operations and q shapes, the total classes required for implementation would be the cartesian product $p \times q$. Due to the class explosion this solution was quickly dropped.

The second alternative that avoided this class explosion was to use templating. Essentially we could parameterise our `Draw` and `Modify` objects with a concrete descriptor. We decided not to use this alternative as templating makes the event classes too generalised.

Another alternative we looked into was to create a log of events containing copies of the items instantiated on the canvas. In Section 5.1.2 we talk about keeping our project independent of Qt's implementation as much as possible. Clearly recording copies of instantiated Qt objects violates this principle and would potentially result in a cascade of changes throughout the system, including serialisation code.

3.2.2 XML Logging to Disk

We settled upon using XML to describe the history of the log by representing the parameters required to reconstruct an object, as well as any modifications which may have occurred to that object.

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE tabula>
<tabula version="1.0">
  <log size="1">
    <draw>
      <desc type="rect" x="108" y="90" width="177" height="168">
      </desc>
      <event owner="You">
        <timestamp size="1">
          <localtime value="1"></localtime>
        </timestamp>
      </event>
    </draw>
  </log>
</tabula>
```

Figure 11: An example XML log as outputted by our project for a single draw event. Note the human readable format: A single draw event for a rectangle positioned at (108,90) with a width of 177px and height of 168px. This also contains the event information including the owner and timestamp.

We are using XML to record data to disk as it is a well known, general-purpose specification for creating custom markup languages designed for transporting and storing data[37]. XML provides for several useful features, including DTD validation to define a legal XML document for a system[5] to ensure the file can be parsed correctly. We currently do not use DTD validation as Qt's XML implementation does not currently support DTD validation, however as we shall be generating the log files in a strict manner they should never produce an invalid XML log file. We eventually aim to include DTD validation in a future release of the project, especially if our log files are to be used or extended by other applications, but it is not of significance to the current release.

XML is a highly verbose method of describing data. We see this as a good feature for logging to disk as we can record data in a human readable form, as can be seen in Figure 11. This is beneficial in avoiding what is known as the "Digital Dark Age" where old and obsolete file formats become unreadable as, if necessary, our logs could be interpreted manually. A famous example of this is NASA who have data collected from the 1976 Viking landing on Mars stored in formats which they can no longer interpret[20]. This also allows for future extensibility for other projects to use and interchange log files with our own.

3.3 Chat Subsystem

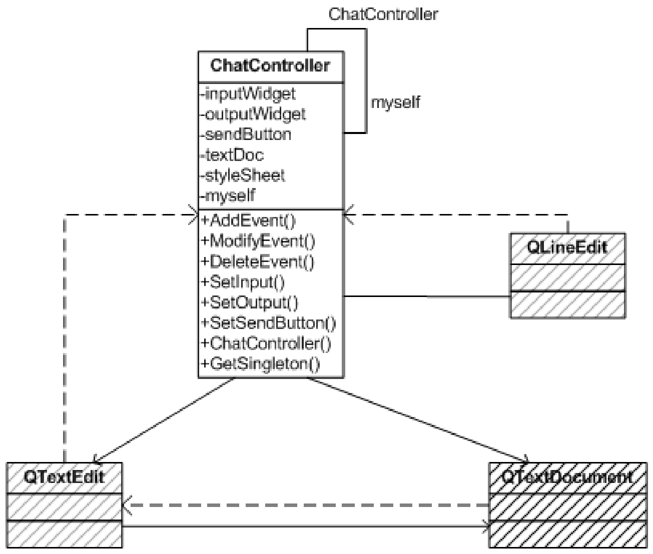


Figure 12: Class diagram showing our chat controller.

The chat system implements the MVC pattern as discussed in Section 3.1.1. We have a controller (`ChatController`) for interfacing with other subsystems, a **Model** (`QTextDocument`) to store an internal representation of the data and a **View** (`QTextEdit`) to display the chat history. This design allowed us to freely interchange the view component used, reducing coupling as discussed in Section 3.1.1. We settled on the `QTextEdit` object as this allowed us to apply formatting through the use of CSS stylesheets to the data. The alternative to this, which we originally implemented, was to use the `QPlainEdit` class which has no support for formatting.

The chat system accepts `Event` objects which are forwarded to it from the log system. The `Controller(ChatController)` unpacks these `Event`s and extracts their information, this method implements the **Expert Principle**. This data is then added to the model by the controller in the form of a `String`. The view automatically updates when data is added to the model, however the controller ensures the view conforms to the conventions of other IM clients (such as Windows Live Messenger from Section 1.4.1) by scrolling the view to the bottom to track the most recent message.

The text view widget is set to read only to prevent the user from accidentally entering text. The input widget accepts the [Enter] key as an alternative to pressing the ‘Send’ button to relieve the expert user from having transition from keyboard to mouse to perform this action. The `ChatController` is implemented as `Singleton` to allow the log to obtain access to it, this ensures only one instance of the chat system is ever present in a particular session.

3.4 Board Subsystem

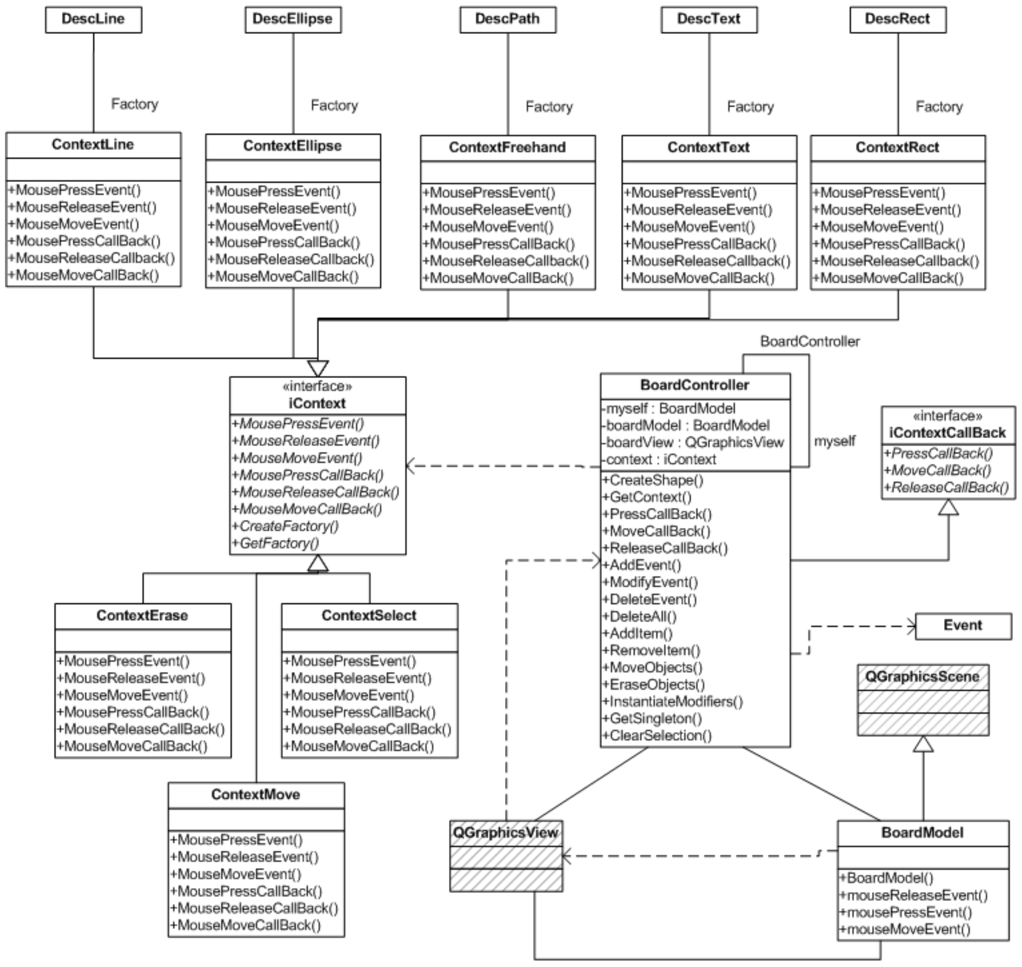


Figure 13: Class diagram showing the use of contexts for object creation. As can be seen, `BoardModel` methods correspond directly to a subset of those in `iContext`.

The Board subsystem is responsible for displaying and manipulating graphical data on the screen. Qt provides a set of classes which we used and extended to implement this. We will now cover the implementation of the board's graphical system, referencing Figure 13.

3.4.1 Overall structure

The board system implements the MVC pattern as discussed in Section 3.1.1. We have a controller (`BoardController`) which we implemented from scratch for interfacing with other subsystems, a model (`BoardModel`) which derives from

`QGraphicsScene` and a view (`QGraphicsView`), which was implemented for us, to display the graphical objects.

3.4.2 View

The implementation for `QGraphicsView` automatically listens for mouse input from the user. When mouse input is detected, all information about the mouse input received (including screen co-ordinates, button pressed etc.) is encapsulated in a `mouseEvent`, which is then passed to the appropriate mouse method in the model. The view is automatically updated as items are added to the board via the model.

3.4.3 Scene/Model

The `QGraphicsScene` class behaves as a model and comes with a default implementation for mouse events whereby any mouse event forwarded to it by the view is then forwarded to the topmost item underneath the cursor. This implementation is useful to perform general operations on any object (repositioning for example), but it is not sufficient to facilitate the drawing of objects onto the canvas by the user.

Our `BoardModel` class provides this functionality by overriding the `QGraphicsScene`'s `mouseDown()`, `mouseMove()` and `mouseRelease()` methods. We can then forward the `mouseEvent` each of these methods receives to any class of our choice, finally calling the superclass of `BoardModel` passing the `mouseEvent` in order to get existing objects on the board to respond.

3.4.4 Graphic Items

Qt defines a family of shapes which all inherit the `QGraphicsItem` class, these provide a default implementation for the basic set of shapes we need and are responsible for drawing themselves to the canvas. The `BoardModel` is capable of accepting and returning `QGraphicItem` objects and any subclass. We describe how to extend this basic implementation in Section 3.4.5.

3.4.5 Identifying Graphical Items

During a drawing session, many `QGraphicsItems` are created by multiple users on a canvas. Traditionally a local system would reference these through pointers, however these are simply local memory addresses which become meaningless on a remote system and we require a more robust method of referencing our `QGraphicsItems`. In general, this applies to all objects which must be both passed over the network which are referenced at a later time. To solve this we use Timestamps, discussed in further detail in Section 4, to uniquely identify each object by creating a logical ordering for each `QGraphicsItem` which is consistent across all instances. Due to this ordering, we are able to treat a timestamp as a globally unique identifier for any `Event` and associated `QGraphicsItem` in the system.

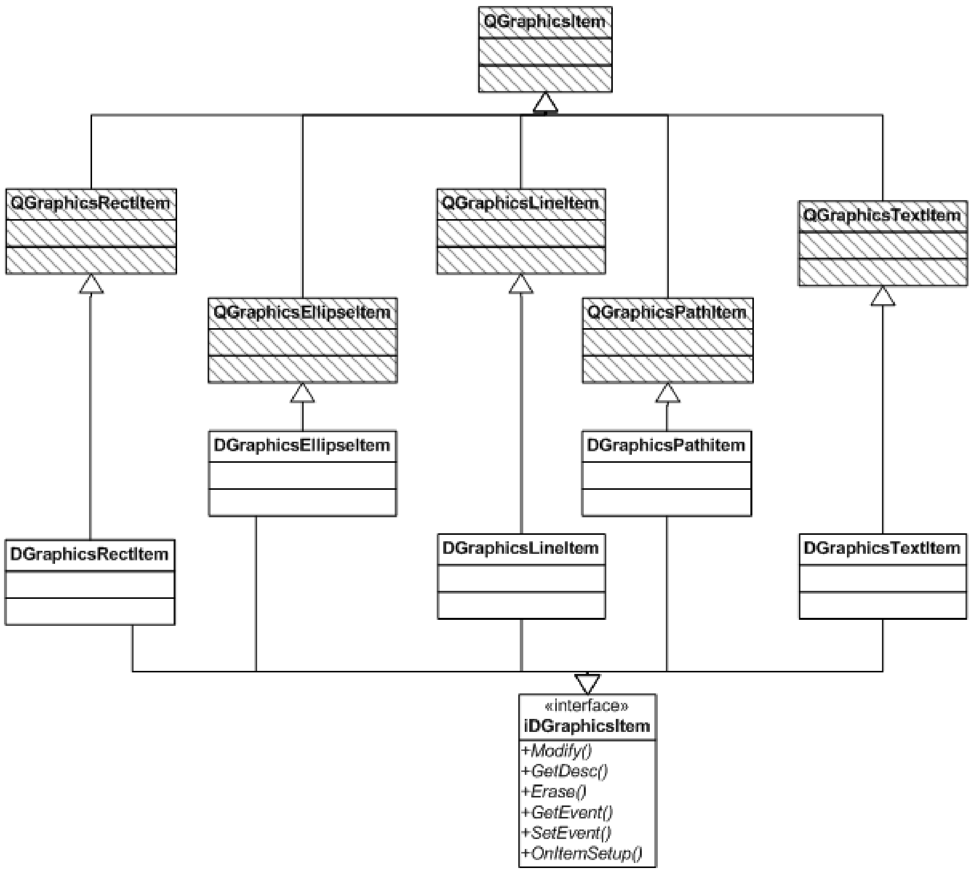


Figure 14: Class diagram demonstrating a method of extending `QGraphicsItem` functionality using multiple inheritance to create our concrete Distributed Graphics Items

Our first problem was finding an elegant way to relate this unique identifier (timestamp) to our `QGraphicsItem`s. Making use of C++'s multiple inheritance we are able to create our own Distributed Graphics Item class (`DGraphicsItem`) to hold our extended properties and methods, we then use this in parallel with Qt's abstract `QGraphicsItem`. We then subclass each of the four concrete `QGraphicsItem` classes thereby inheriting our new `DGraphicsItem` class and all of its features, as can be seen in Figure 14. Note that virtual multiple inheritance cannot be used here and we require a special class to cast `QGraphicItems` into `DGraphicItems`.

Finally, we abstracted away the use of Timestamps by creating a mapping of Timestamps to pointers at the log level. This means that the programmer does not need to have knowledge of how we use Timestamps to identify objects and can simply use local pointers. This decision was taken to increase the extensibility of our project.

The board model will still accept these items since all concrete implementations of `DGraphicsItem` will still inherit from `QGraphicsItem`.

3.4.6 Casting

Because we can't implement the diamond pattern we identified in Figure 5 we have to improvise using a dynamic cast which checks if it's possible to cast, if not it returns NULL as failure. In our view, casting is a viable but not such an architecturally beautiful approach; if Qt release a new `QGraphicsItem` type, we will have to modify all casting scattered code around the project. This potentially violates the closed for modification principle we aim to adhear to, we can however mitigate its effects by ensuring all casting code is kept to one special `Casting` class. In this way we would only have to modify the internal workings of the `Casting` class and all objects that use this class can remain closed for modification.

3.4.7 Drawing Contexts

We provide the user with a variety of tools with which they are able to use to manipulate and create shapes on the canvas. The actions required by the user to operate such tools is consistent: positioning, drawing and erasing an object should be the same for an ellipse, square or line. However we require different algorithms to draw different objects, for example the coordinate data sent from a mouse move event will be interpreted differently when drawing a line compared to drawing a circle.

As developers we would like to make the algorithms for generating a square or an ellipse as interchangeable as possible to maximize code re-use whilst still maintaining encapsulation rules. Furthermore we must bear in mind the extensibility of our system and ensure that adding new algorithms, such as for custom shapes, require the least amount of code alteration. To this end, we used the **Strategy Pattern** which uses delegation to achieve this flexibility in behaviour.

As shown in Figure 13 we define a family of algorithms which we refer to as ‘contexts’. Each concrete `Context` corresponds to a tool from the palette (square, ellipse, erase) which derives from an abstract `Context` and is responsible for handling the mouseDown, mouseMove and mouseRelease events for that tool. The board controller maintains a reference to the current context and passes these mouse events through to the appropriate handlers.

3.4.8 Factory Within Contexts

Each context receives mouseDown/Move/Release events from the `BoardModel`, essentially it now becomes the responsibility of the context to know what objects to create when the mouse is first pressed. Hence, each context also has a factory method to create the correct objects.

We now have a very flexible, extensible way of creating objects on the board which allows for interchanging creation and interaction algorithms.

3.4.9 Executing Board Events

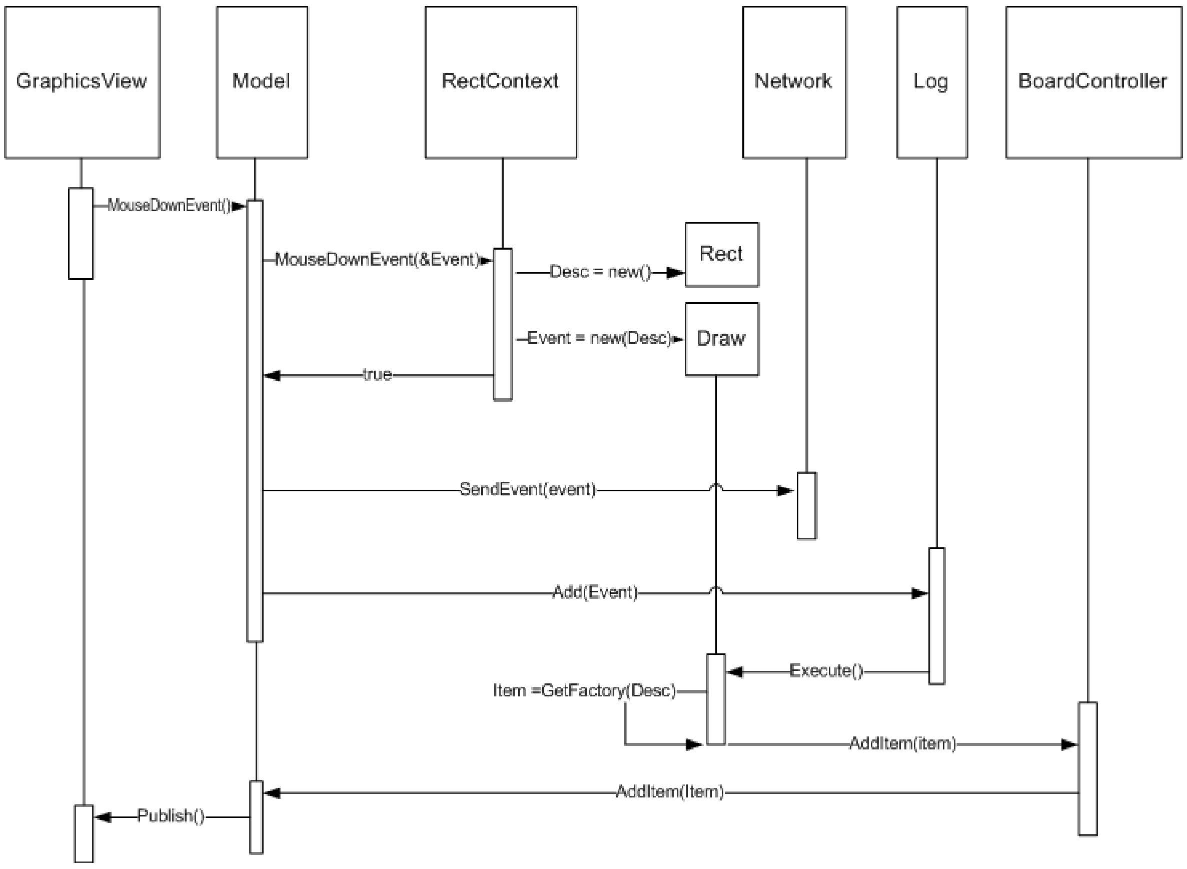


Figure 15: Sequence diagram showing procedure calls required to process a rectangle draw event. This sequence follows the actions of dropping a rectangle onto the canvas. The user has already selected the rectangle tool from the palette.

The abstract `Event` class discussed in Section 3.2.1 defines an `execute()`

method, the body of this method is implemented in every concrete `Event` class. Each class should know which controller to call back. For example, a draw `Event` would know to call the `BoardController`'s add method in order to add a graphic item. Contrast this with a chat `Event` which would know to call back the `ChatController`. The actual callback is implemented with a `Callback` class, this ensures an extra level of indirection to decouple the subsystems from each other, nevertheless the intention is the same. In all cases, to call `execute()` the log need not know about concrete board event related classes, only that they are `Event`s.

The purpose of the execute method is to call the appropriate controller, passing the required information to instantiate a graphics object. For example, the `BoardController`, when passed a draw `Event` would call a factory passing the descriptor. The factory would then instantiate the graphics object based on the information contained in the descriptor. When the item has been returned by the factory the graphic would be added to the `BoardModel`.

3.4.10 Calling Order

For clarity we now outline a concrete example of the user drawing a rectangle on the board. Figure 15 contains a sequence diagram to be read alongside this section.

The user clicks the 'Draw Rectangle' button from the toolbar, this causes the `BoardController` to change its context to the `SquareContext` (Note, this step is not in Figure 15).

When the user clicks on the board the view calls `BoardModel::mouseDownEvent(mouseEvent)` passing details about the `mouseEvent`. The `BoardModel` then creates a NULL pointer to an `Event` and forwards this by reference to the context via `context->(mouseDownEvent(mouseEvent),Event)`. The `mouseDownEvent()` in the context knows to instantiate an `Event` and assign it to the `Event*` parameter.

The `BoardModel` now has a draw `Event` and needs to dispatch this to the `Network`. The `Event` object is responsible for serialising itself, through use of the expert principle, and the `Event` in turn asks its `Descriptor` to serialise itself. This serialised `BitStream` data is then sent over the network and the `Event` is added to the `Log`. By keeping the serialisation call inside the `Event` class, we are abstracting away details about serialisation and BitStreams from the user of the `Event`. Essentially the programmer can send the event by just calling the events's `SendEvent()` method. This also keeps the BoardModel more cohesive since it is not charged with the task of calling serialisation methods.

When the `Event` is added to the log its execute method is called and it uses the callback system to contact the `BoardController` passing the `Event`. The `BoardController` then unpacks this event, instantiates the graphical item according to the descriptor and adds the rectangle to the model. The model then updates the view automatically via an internal publish method.

3.5 Network Subsystem

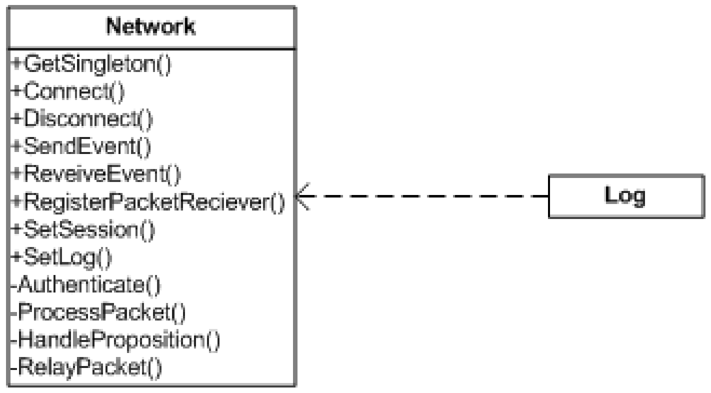


Figure 16: Network subsystem class diagram.

The network subsystem exists to allow the sending and receiving of messages over the network. It allows the programmer to abstract away the details of serialising `Event` objects and broadcasting them across the network by providing a method for BitStream dispatch and supporting callbacks for receive implementations in the rest of the program. Essentially the object is serialised and sent, then on receive the object is passed as a parameter to the receive callbacks where it is deserialised and made available for use by the developer. We explore the network subsystem's implementation in further detail in Section 6.

3.5.1 Serialisation

In Section 5.1.2 we talk about how `Event` object contain `Descriptor` objects and explain that the network sent these using serialisation. We cover serialisation in greater detail in Section 5.5, but for now we state that the responsibility for this operation is held by the object being serialised based upon the Expert Principle. This ensures that should the implementation of the descriptor or event change, the effects (changes in serialisation method) will be confined to a single class.

Serialisation of events is recursive, so the serialise method in `Draw` calls the serialise method in the `Descriptor` it contains, the `Descriptor->serialise()` result is propagated and appended to the serialised draw `Event`.

3.5.2 Session

We require a list of current participants in the session to display chat information and provide user feedback. We follow the conventions of Windows Live Messenger and **Internet Relay Chat (IRC)** where a list of currently active participants is visible on either the left or right hand side. As in the other subsystems, we facilitate the display of this information via the MVC pattern.

The network comes equipped with a `Session` class which maintains a list of all the users in the current session. Both the network and the log require access to this system since both need to identify the source of events.

Our `Session` class contains a vector as a record of all active participants, each entry represented by a `Person` object. A `Person` object contains information about the participant including username and systemId (see Section 6). The display of lists in Qt can be implemented with the `QListItems` component, so we again implement the MVC architecture. We require a model to hold the data to be displayed and already have our vector container, however, the encapsulating `Session` class requires some modification before we can make use of our existing model.

3.5.3 Session View

The view is implemented as a `QListItems` class provided by Qt. Although we do not implement the display of avatars next to the name in our implementation, we wish to support this feature as a possible extension. The `QListItem` widget provides a way of displaying textual information along with optional icons. Since `QListItem` accepts objects of the `QVariant` type, it is possible to implement associated images using this class. This makes our view extensible should we choose to extend our application in the future to support avatars. The other option which we did not explore further was to use a `QStringList` which doesn't use MVC and doesn't support avatars.

3.5.4 Session Model

The `QListItems` view is supported by an implementation of `QAbstractListModel`. The concrete implementation of this requires 2 methods; `data()` and `rowCount()`. Our `Session` class is defined by the `iSession` interface, therefore we use C++'s multiple inheritance to derive a concrete implementation of `QAbstractListModel` in the `iSession` interface. `Session` will then implement these two methods and allow us to use session as a model.

The data function is called when the view needs to gather display data. It is capable of responding to many requests for data including tooltips and size hints. We will be ignoring all requests except for `Qt::DisplayRole` since this is the request for handling textual display data. The index parameter maps directly to the index of our `Person` vector and so we can simply return the username of the person at that index as a `QString` (Subclass of `QVariant`). When returning we must ensure the index is valid and return an empty `QVariant` for both the invalid case and ignore request response.

When data is added to the model, we simply call `reset()` to perform a full refresh on the view. It should be noted that calling a full reset is a costly operation and is a shortcut to evaluating the index of the changed data. This is only deemed acceptable in this case because the size of the list is expected to be small (<10), updates are infrequent and the source data is local. `Reset()` of larger or remote lists (e.g. one requiring an SQL lookup) can bring about performance issues and should be avoided.

3.6 GUI Design

As the streamlined integration of chat, drawing and the ability for multiple users to contribute doesn't appear to have an existing product, GUI design is an important element of our project. The HCI of the solution had to be considered carefully to take maximum advantage of the user's pre-existing cognitive models for graphics applications.

The menu bar along the top is one of the most common features of applications so there was no reason to change this as it could cause confusion among some users; many people dislike the 'ribbons' used in MS Office 2007 and find that it does in fact lower productivity with some options taking more mouse clicks to perform that in previous verions os Office [8],[28]. We have a simple, standard File menu along the top of our application to facilitate this.

In keeping with text chat conventions the integrated chat consists of a session log in a scrollable window, placed above a text entry field. This entry field has a 'Send' button which greys out when not available and can also be triggered by the [Return] key. There are no such conventions for integrating chat and drawing that seem applicable to our application, hence we placed the chat dialog below the canvas as it is the secondary area of focus. This is similar to the way iScribble, the only similar application, integrates these two features.

In the analysis of similar applications in Section 1.4 it was found that drawing toolbars appeared at the top of the drawing canvas. However, we also found that these applications failed to provide an adequate selection of drawing tools. We have instead decided to follow the conventions of standalone drawing applications such as MS Paint, Photoshop and the GIMP which more closely match the array of tools we wish to make available. These applications typically have a vertical panel to the left of the drawing canvas, hence our tools are placed in the top left section of the GUI.

An initial layout of the GUI was developed as in Figure 17. This was subject to change as more was learnt about what the final user base may be and also the number of users who would be in the same conversation at any one time.

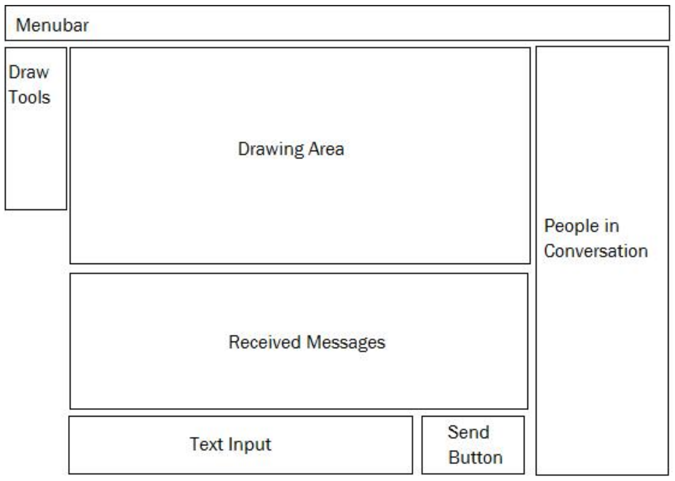


Figure 17: Initial GUI design.

The only real change to this layout was the size of the 'People in conversation' area. It was decided that the solution would not support avatar images for users or any other form of identification other than a simple username. Also, it was clarified that the expected number of users in a session would be relatively small, maybe up to 10. This meant that a large portion of the space taken up by the 'People in conversation' area was being wasted. This led to the second and final version of the GUI. By resizing the 'People in conversation' area down to below the bottom of the drawing area, the drawing area could be extended, giving a greater visible area of the canvas. The final GUI design was approved

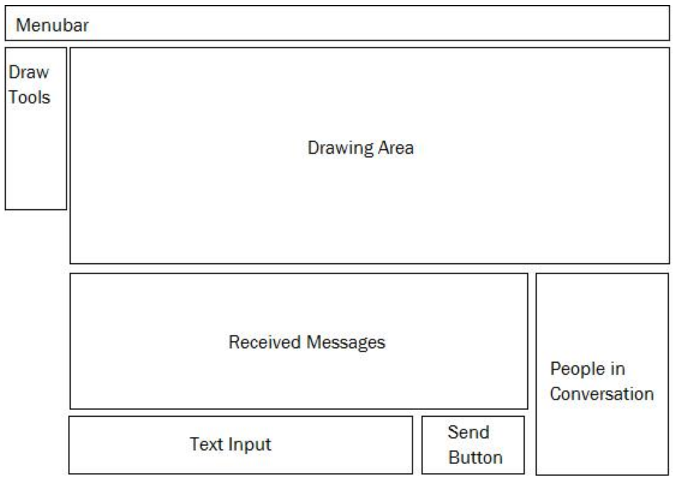


Figure 18: Final GUI design.

by the project supervisor before work continued. It was very important to get the GUI correct at this early stage as if the user wanted more options located on toolbars, or hotkeys for options, this would likely change the design of other parts of the solution, for example, it may become necessary to use a `QAction` to keep menu bar options and toolbar options in sync.

3.7 Exporting to Image File

As part of the requirements we must consider how to export the contents of the board to an image file.

3.7.1 JPG/JPEG Plugin Issue

Initially we aimed to export the image as JPG/JPEG and encountered problems where an output file would be created but contained no data. This was because we did not deploy image plugins with the application. To solve this one could copy the contents of plugins/imageformats directory of the Qt installation to the imageformats subdirectory of the directory where the application binary is located. This issue is true of JPG/JPEG, SVG and TIFF formats.

To minimize our dependency on extra libraries and plugins and to reduce complexity, we chose not support the exporting of images to JPG, instead choos-

Format	Description	Qt's support
BMP	Windows Bitmap	Read/Write
GIF	Graphics Interchange Format	Read
JPG/JPEG	Joint Photographic Experts Group	Read/write
PNG	Portable Network Graphics	Read
PBM	Portable Bitmap	Read
PGM	Portable Graymap	Read/write
PPM	Portable Pixmap	Read/write
TIFF	Tagged Image File Format	Read/Write
XBM	X11 Bitmap	Read/write
XPM	X11 Pixmap	Read/write

Table 2: Formats supported for export and import in Qt 4.4 using the `QImage` class.[32]

ing the PNG format as the most suitable due to its typically small size combined with high quality image and widespread use.

3.7.2 Implementation

Following conventions of popular photo editing software, we chose to have an 'Export to image' entry on the file menu. When you click this the native save dialog box of the host operating system is invoked; this ensures portability. The dialog box is invoked as a modal instance to ensure that the dialog is not lost behind the application and maintains foremost focus. If the filename returned is not empty, we instantiate a stack instance of the `QImage` class and assign it a `QPaint` class. The `QImage` class provides the export format functionality, while the `QPaint` class is used by the `BoardModel` to render the given sceneRect.

It is important to note that the `render()` is called on the `BoardModel` and not on the `GraphicsView` (which also has a render function), calling it on `GraphicsView` will typically capture the viewport area and not the entire scene. When `save()` is called, the `QImage` exports the data to the filename in the dialog box and the export process is complete. The function returns and since the entire process was done with stack objects, we need not concern ourselves with deletion of objects.

3.7.3 Right-click Context Menus

We frequently wish to do things specific to a `GraphicsItem` and don't want to waste GUI real estate. For situations like this we can design a popup menu with options relevant to all `GraphicItems`. This is where we implement locking (permissions), Z-ordering (layers) and resizing in the GUI.

The Boardmodel is set up to check for right-click events. If a right-click occurs and an item is under the cursor we instantiate a right-click menu, passing the pointer to the `DGraphicsItem` under the cursor. This right-click menu can have other items added to it, a very quick way of adding functionality to the system. We shall now explore the three menu items within our context menu.

Locking: Every `DGraphicsItem` contains a boolean lock value. By default it is set to `FALSE` (unlocked), a mode allowing anybody to modify the item. When the right-click menu is instantiated it is able to check the `DGraphicsItem` by the pointer passed to it, lookup the lock value and set the menu checkbox for locked accordingly. If the locked link in the menu is clicked we update the `DGraphicsItem` accordingly. A Modify event containing the appropriate descriptor, with the new lock value, is emitted. This is passed over the network and processed accordingly. When any user tries to move the object, the move request will be handled only if the object is unlocked.

Z-Ordering: `QGraphicsItem`s implement a Z-ordering property. Using an almost identical implementation to the locking system we adjust the Z-order according to whether the increase or decrease link is selected. This shows the simple extensibility the **bridge pattern** gives our implementation for additional properties.

Resizing: Traditionally, vector resizing is done by selecting the item and dragging one of many handles on it. `QtGraphicItems` do not implement this, so we opted for a resize item which presents a dialog box with a horizontal and vertical widget present. As you adjust the horizontal and vertical sliders, the shape adjusts its size. We set the opacity of the widget to be 0.5 giving a translucent effect, allowing the user to see the shape should it disappear behind the popup window.

When the dialog box is instantiated it is passed a reference to the object it is resizing, it is therefore able to call the object back with values for the horizontal and vertical scrollbars. The item can then use these numbers to resize itself appropriately using knowledge principle. Lines use these numbers to adjust its x2,y2 position, whereas a rectangle or ellipse would use this to adjust the width and height.

The dialog is not modal and hence we can right-click and invoke multiple dialogs for other `DGraphicsItems` on the board. The user may find this useful to set an optimal meeting point for two shapes simultaneously, thus making up for not having followed conventions.

4 Timestamps

4.1 Requirements

One part of the project is the history view, in which you can see what happened on the canvas and in what order it happened. For that case we have to be able to analyse the order in which events happened though they happened on different computers. Another issue is pointers, both the `Modify` and `Delete` objects need to reference the `Draw` actions they apply to which have to be serialised and sent across the network, so we need unique identifiers for events in order to reference them consistently across all **peers**.

Ordering events in distributed systems poses some problems. As events can happen anywhere in the system, it might be tempting to attach the timestamp of a local clock to the event and sort events according to these timestamps. But since every process in a distributed system has its own individual clock, showing an individual timestamp and running and at an individual rate, the result might be inaccurate or even completely wrong.

The log in Tabula is keeping track of all `Event` objects in a conversation. Those events can happen anywhere in the distributed system, so we were confronted with the previously described problem when designing the log.

Fortunately that problem is very well examined by Leslie Lamport[22], Friedemann Mattern[24] and Colin J. Fidge[9][10]. Leslie Lamport introduced a very basic version of logical clocks, but he was the first to reason about logical time in systems without a common timebase, so we adapted his notation to our needs. Friedemann Mattern extended Lamport's work to vector clocks, which we are actually using. Lamport's logical clocks were based on natural numbers and do not generate unique timestamps, whereas Mattern's vector clocks are still easy to implement yet are even able to express concurrency.

In the following we will try to give an understanding of the logical timestamping we are using and demonstrate that it will be sufficient to order the events that occur in Tabula. Detailed formalism and proofs are available in the original papers.

First we will examine the "happens before" relation operating on events in the system ($\rightarrow$), then we will look at the "happens before" relation operating on timestamps of real clocks ($<$). The goal is to develop a model of real time – logical time – so that we can find a **Homomorphism** between the relation on events and the relation on time.

4.2 Ordering of Events

Leslie Lamport defined events to be anything interesting happening in the system including sending and receiving of messages. He defined '$\rightarrow$' as following: $a \rightarrow b$ if

- a and b are events in the same process and a precedes b, or
- a is the sending of a message and b is the receiving of that message, or
- there is a c, for which $a \rightarrow c$ and $c \rightarrow b$.

Lamport's definition is based on general distributed systems exchanging messages every now and then. Since in Tabula the creation of an event is directly connected to its distribution through the network, we do not need to consider the sending of an `Event` as an action itself, but instead we consider the creation and sending of an `Event` as the same occurrence.

Furthermore we do not consider the receiving of messages being events because that point of time is of no interest to us. The only interesting timestamp is the timestamp of the event we were receiving via that message.

Intuitively $\rightarrow$ is irreflexive ($a \not\rightarrow a$), as time is continuously ticking, and transitive ($a \rightarrow b \wedge b \rightarrow c \Rightarrow a \rightarrow c$), so '$\rightarrow$' is a partial order. If neither $a \rightarrow b$ nor $b \rightarrow a$, then we call a and b concurrent: $a||b$.

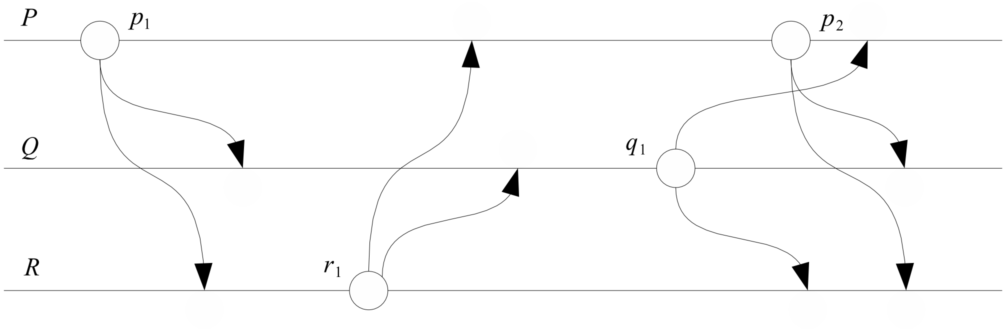


Figure 19: An abstract representation of events happening in a system consisting of three instances of Tabula.

For instance in figure 19 you can see timelines of three processes in the system showing where and when events happen and where and when messages are sent and received.

You can see that $p_1 \rightarrow p_2$ and $p_1 \rightarrow r_1$. But you see that neither $q_1 \rightarrow p_2$ nor $p_2 \rightarrow q_1$, because they neither happened in the same process nor was a message sent and received between the actual occurrence of the events. In that case we say the events happened concurrently: $q_1||p_2$. The fact the system cannot distinguish the time at which both events happened does not mean they happened at the same time. So if C is a real clock assigning timestamps to all events in the system, then $C(q_1) < C(p_2)$. The problem is that we do not have such a clock because every system has its individual clock.

4.3 Logical Time

Talking about real time, we know time is irreflexive and transitive. Moreover, it is linear (it is ticking forward, never backwards), eternal (you can always find an earlier or later timestamp), and dense (you can always find a distinct timestamp between two timestamps).

The most obvious models satisfying those axioms are $\mathbb{Q}$ and $\mathbb{R}$, but we have to consider precision is limited in computers and looking at the real world, we see that there are digital clocks and discrete timestamps. So we try dropping the property density and use discreteness instead, so we might as well use $\mathbb{Z}$.

Though time is eternal, in a distributed system we are not interested in all periods of time, we are only interested to points of time after the start of the system. So we can use $\mathbb{N}$. Again considering the limitation computers impose we are not able to represent whole $\mathbb{N}$, but in reality we can hardly produce so many events such we reach those limitations.

So the main difference between logical time and real, physical time is that while real time is continuously flowing, logical time only ticks when something happens, like for example a shape is drawn on the canvas. Another difference is that there is no common sense of time, but every process will have its individual local clock.

To construct a clock we have to think about what conditions it has to fulfil. Leslie Lamport defined a fairly weak condition (in which C is the local clock of the process the concerned event happened in):

Condition. *For all events a and b, the following holds:*

$$a \to b \quad \Rightarrow \quad C(a) < C(b)$$

In this case '$<$' is the usual less relation on natural numbers.

That condition can be satisfied very easily. As Lamport only dealt with natural numbers he defined clock operations in two cases:

Definition. *The local clock C_i of the process P_i behaves as follows:*

- *When an event occurs or a message is sent, the clock ticks:*

$$C_i := C_i + \delta \qquad (\delta > 0)$$

- *When a message sent at time t is received the clock is synchronised and ticks:*

$$C_i := \max(C_i, t) + \delta \qquad (\delta > 0)$$

The choice of δ is free. It might always be one, but it also might be different every clock tick, for example approximate real time.

So far the partial ordering of events is imposed on the timestamps of Lamport's logical clocks. But concluding some ordering from the timestamps is not possible. The reason for that is, that Lamport constructed a **Weak Homomorphism** from $(\mathcal{S}, \to)$ to $(\mathbb{N}, <)$, where $\mathcal{S}$ is the set of all events in the system. It is easy that a **Strong Homomorphism** cannot exist.

4.4 Vector Clocks

Friedemann Mattern extended the timestamps from natural numbers to vectors of natural numbers, where each component represents the state of a local Lamport clock. The idea is you can define time cuts through the system by noting down the timestamps of the local Lamport clock along the cut into a vector. Because a processes does not have knowledge of the states of the clocks of other processes, but it can approximate them when timestamps are sent along messages.

This way we will be able to satisfy the strong clock condition:

Condition. *For all events a and b, the following holds:*

$$a \rightarrow b \quad \Leftrightarrow \quad C(a) < C(b)$$

$$a || b \quad \Leftrightarrow \quad C(a) || C(b)$$

In this case '<' does not operate on natural numbers anymore, but on vectors, therefore we define it in the following way.

Definition. *For two timevectors u and v let*

- $u \leq v \quad :\Leftrightarrow \quad \forall i : \quad u[i] \leq v[i]$
- $u < v \quad :\Leftrightarrow \quad u \leq v$ *and* $u \neq v$
- $u || v \quad :\Leftrightarrow \quad u \not< v$ *and* $u \not> v$

Mattern adopted Lamports clock rules except for the fact that timestamps turned into vectors and each process only modifies its 'own' component of the vector on a clock tick:

Definition. *The local clock C_i of the process P_i behaves as follows:*

- *When an event occurs or a message is sent, the clock ticks:*

  $$C_i[i] := C_i[i] + \delta \qquad (\delta > 0)$$

- *When a message sent at time t is received the clock is synchronised and ticks:*

  $$C_i := \max(C_i, t); \qquad C_i[i] := C_i[i] + \delta \qquad (\delta > 0)$$

  (where max *is a componentwise operator on vectors).*

The important fact is that only process P_i modifies the i-th component of its local time. That way P_i holds the most recent knowledge about the i-th component of global time and other processes will update their knowledge about than component when receiving messages.

4.5 Implementation

In our implementation of timestamping we use a slightly modified version of Mattern's vector clocks. As we are not interested in the timestamp of sending or receiving messages we do not tick clocks in that case. We only tick a clock to create a fresh timestamp to attach it to a new event, this avoids wasting timestamps. This has an impact on the behaviour of vector clocks:

Definition. *The local clock C_i of the process P_i behaves as follows:*

- *When an `Event` occurs, the clock ticks and the new timestamp will be attached to it:*

  $$C_i[i] := C_i[i] + \delta \qquad (\delta > 0)$$

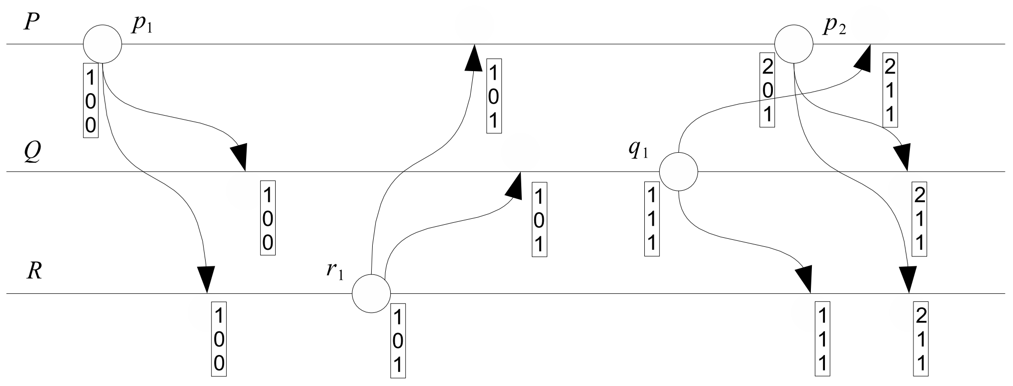


Figure 20: A sample run showing the state of local clocks and timestamps attached to events.

- *When an* `Event` *which occured at time t is received via network, the clock is synchronised:*

$$C_i := \max(C_i, t)$$

(where max *is a componentwise operator on vectors).*

In Figure 20 there are the states of the local clocks noted in rectangles next to the timelines of the processes, whereas the circles represent occurring `Events`. You can see the updating of local clocks whenever a message is received (componentwise maximum between the current state of the local clock and the timestamp of the received `Event`). You can also see the local clocks ticking (increasing its own component) whenever an event occurs, those new timestamps will be attached to that event, so the receivers of the broadcasted events can synchronise their clocks.

Also note that since every process only increases its own component, one process will never be able to create timestamps another process could create. Moreover clock never tick backwards, so no process can create a timestamp twice. Thus the attached timestamps are unique throughout the whole system.

Implementing the ticking of the local clocks is fairly straight forward. The key is having a unique id for every instance of Tabula in the network, so you know which component of the timestamp to increment. You also have to ensure the vector is big enough so the component you want to increment actually exists.

```
Timestamp& Timestamp::operator++()
{
  if( time.size() <= Log::GetSingleton().GetClientID() )
    time.resize( Log::GetSingleton().GetClientID()+1, 0 );

  ++time[ Log::GetSingleton().GetClientID() ];
  return *this;
}
```

The synchronisation of a clock is easy too because it's just a componentwise maximum function. We have to be concerned about the size of the time vector because new people might have joined the session.

```
void Timestamp::Update( const Timestamp& ts )
{
  for( unsigned int i = 0; i < ts.time.size(); ++i )
  {
    if( i >= time.size() )
      time.push_back( ts.time[i] );
    else if( ts.time[i] > time[i] )
      time[i] = ts.time[i];
  }
}
```

The toughest part of the class is comparing timestamps. The idea is to compare the two vectors componentwise and assume missing entries to be zero. We save if there were smaller, greater or equal components and base the result of the comparison on those three booleans. In order for the two timestamps to be the same all components have to be equal. In order for one timestamp to be earlier than another there has to be a smaller component, there might be equal components, but never greater components. When a timestamp is neither the same, nor earlier, nor later than another, they are concurrent.

```
Timestamp::CompareType Timestamp::Compare( const Timestamp& ts ) const
{
  bool smaller = false;
  bool greater = false;
  bool equal = false;

  Vectortime::const_iterator it1 = time.begin();
  Vectortime::const_iterator it2 = ts.time.begin();
  while( it1 != time.end() || it2 != ts.time.end() )
  {
    Localtime t1 = 0;
    if( it1 != time.end() )
    {
      t1 = *it1;
      ++it1;
    }

    Localtime t2 = 0;
    if( it2 != ts.time.end() )
    {
      t2 = *it2;
      ++it2;
    }

    if( t1 < t2 )
      smaller = true;
    else if( t1 == t2 )
      equal = true;
    else
      greater = true;

    if( smaller && equal && greater )
      return concurrent;
  }

  if      ( !smaller && !greater && equal )
    return same;
  else if(  smaller && !greater )
    return earlier;
  else if( !smaller &&  greater )
    return later;
  else
    return concurrent;
}
```

5 The Log

The log contains a store of `Event` objects (Section 5.1) that have occurred within the current session (Section 6.2.3). It keeps track of the current event state and provides methods for fast `Event` searching and jumping (Section 5.3) between event states.

5.1 Events

`Event` objects represent changes between session states. They are stored in the log, ordered by a timestamp (Section 4). Each `Event` contains references to its previous (parent) and future (children) `Event` objects. The `Event` class provides the common functionality of all `Event` objects (owner recording and timestamping) and is inherited by each `Event` type where it is extended with specific functionality.

Furthermore the Event class declares undo/redo methods, used by our history functionalities.

5.1.1 Chat Events

Chat `Event` objects contain text information and are stored separately in the log to other types of `Event`. This is done because they do not require modification or deletion, so keeping them separate to `Event` objects which do will improve search performance. Each chat event records the sender, the text and the real world time of the message. All three parts are used to construct a text string which is then added to the chat box. When a chat event is received, the send time is converted to local time. This corrects for time zone differences between peers.

5.1.2 Draw Events

Draw `Event` objects are a container for everything which can be drawn on the board. They point both to the graphics item on the board and to a descriptor object which is described in the following.

Descriptor Objects: Descriptor objects describe objects independently of `QGraphics` implementation, so for a rectangle we store its start and end position, along with its width and height. They are only required for `Draw` events. It just so happens that this system maps nicely onto Qt's implementation, but it doesn't have to. If Qt were to change their implementation of rectangles and ellipses it would not affect our descriptor objects since we describe our objects in a human readable form.

Furthermore, descriptor objects contain the minimum information to describe shapes in their 'abstract' implementation which not only makes for efficient data transmission, but also if we were to overhaul our use of Qt's graphic system entirely and revert to some other implementation, our descriptors would be unaffected and sufficient to describe the objects such that they can be constructed in the new implementation. This has the added benefit of our log files remaining valid, not requiring different versions as the software implementation changes.

The alternative would be to attempt to serialise graphical objects themselves, however this leaves us open to the issues raised above, along with pointer problems and such. We would like to not concern ourselves with Qt's implementation of graphical objects as it is rather complex, so the idea of independent descriptors is ideal for us.

5.1.3 Modify Events

Modify events consist of a `Event` pointer and a descriptor object (Section 5.1.2). The `Event` pointer is used to find the `Draw` event that is related to the `QObject` that will be modified, the descriptor object contains a description of the modification that will take place.

5.1.4 Delete Events

Delete events contain an `Event` pointer for the `Draw` event that is to be deleted. The `Draw` event pointer is stored so it can be used on the execution of the `Delete` and for later use, such as when an undo action is made.

5.1.5 Temporary Events

Temporary events are optional and are not kept in the log. They are used for convenience, e.g. so one person in a conversation can see what another person is drawing while he is drawing it. When temporary events are sent across the network we do not ensure delivery or ordering, as they are optional (see Section 6.1.4).

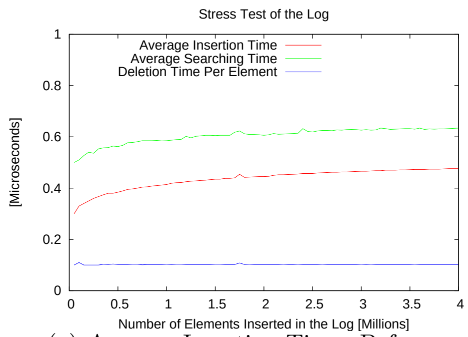
5.2 Adding Events

All added `Event` objects get executed so their changes take place on the canvas. When an event is not temporary we add it to the internal storage. Storage for both `Chat` and other events is a sorted vector for the benefit of search efficiency. Because all added events will be relatively recent we do a linear search from the back of the vector. Furthermore, on `Event` addition the local clock of the Log gets updated, the parent `Event` will be set up and the added `Event` will be added to the children of the parent.

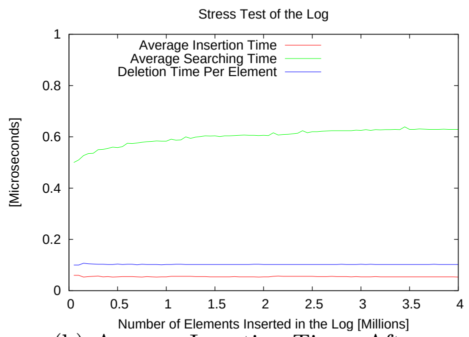
5.3 Event Jumping

As part of the undo/redo system, we have implemented `Undo()` and `Redo()` functions for each event. Using these functions an event can be undone/redone locally without loosing any state information. In effect we are interchanging old and new state information as recorded in a descriptor. To make this state change we walk through the history, undoing when you are walking backwards in history to a common ancestor event and redoing when you are walking forwards. In the case of moving between different branches, we can completely undo one branch and redo another branch. To aid this we added generic walker methods using function pointers to the log, allowing us to walk up and down event branches executing our chosen functions.

5.4 Optimisations



(a) Average Insertion Times Before.



(b) Average Insertion Times After.

In the first versions of the `Log` the search for the right point of insertion of new `Events` was done by binary search, which turned out to be suboptimal. `Events` added usually happened recently, or at least later than the majority of `Events` in the `Log`. So the benefit of a $O(\log n)$ worst and best case complexity is lost when we can do the average case in $O(1)$ with a linear search from the back. Figure 21(a) shows that insertions indeed took about $\log n$ operations. After the optimisation insertion time dropped significantly to a constant time complexity, as can be seen in figure 21(b).

An optimisation made within `Event` provided a significant decrease in our network bandwidth usage. The data used to describe objects and modifications to them were stored in double precision floating point variables, however investigation showed that we weren't using this precision at all. We found that 16-bit integers provided desired precision and range of values. On top of this big saving, compression support for integers was far better than on floating point numbers, giving us an extra saving.

5.5 Serialisation

All `Events` in the system are able to **serialise** and **deserialise** themselves to both a `BitStream` for the network and to XML for saving on hard disk. On serialisation every object writes all its important information to a stream, this can be done directly for atomic types. Classes usually have to implement a serialisation method so they can be written to a stream again. The only exceptions are strings, which can be handled like an atomic type; Qt's graphic items, which are serialised by their descriptor objects (see Section 5.1.2); and pointers to other `Event` objects, which are serialised by their timestamps.

Recursive serialisation is fairly simple as we can override the inherited serialisation function, so the serialisation function of the most specific class gets called, essentially delegating the task and letting subclasses specify. On deserialisation you cannot just deserialise an `Event` from a stream, but you have to decide which kind of `Event` will be instantiated (`Draw`, `Chat`, ...). That process requires knowledge about class specific details outside of the class.

The description objects are responsible for serialising and deserialising every item of information they need in order to reconstruct the related graphics items after deserialisation. For that purpose every description object has a factory method.

Serialisation of pointers to `Events` is very handy. It enables Modify Events to find its graphic item on the board even though it has been send across the network. `Modify` and `Delete` have a pointer to the concerned `Draw` Event, which has a pointer to the object on the screen. Moreover the parent and children pointer for the history functionality are serialised that way.

To deserialise the `Event` pointers we have to search the log for the event with the timestamp read from the stream. We do that with binary search which is implemented in the `upper_bound` STL function. The problem is that the function requires the vector it is searching in to be **strictly weak ordered**. However, timestamps are only **ordered partially**, which means incomparability is not transitive. So we cannot guarantee the success of the search though it usually does succeed. In case binary search is unsuccessful we start a linear search to guarantee a successful deserialisation of the `Event` pointers.

6 Network

6.1 Network Topology

6.1.1 Structure

The network is modelled on a decentralised peer-to-peer structure where any new peer can connect to any existing peer. When a new peer connects to the network, a message propagates to all currently connected peers notifying them of its existence. Each peer keeps a local copy of the current session and peer status (See Section 6.2.3). The new peer joining the network is then sent this information to populate its own list.

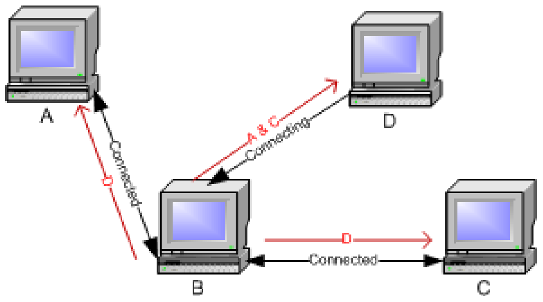


Figure 21: Process of peer D connecting to peer B and the resulting data propogation.

One of the key advantages of the design in Figure 21 over a centralised structure is that it implements a 'NAT punch-through' system.

6.1.2 NAT Punch-through

NAT (Network Address Translation) maps one public IP address to one or more private IP addresses. This is common[7] where many machines are connected in a LAN with a single router providing access to the **Wide Area Network (WAN)**. The NAT contains a table mapping internal machines' requests to external addresses, this is how it knows which machine to route incoming packets to. For this table to be updated with the correct machine to route to, that machine must have first sent a packet to that external address.

NAT can cause many problems for distributed systems due to the inability to communicate with machines with the same external network address before their NAT has been updated with routing information. Consider two machines, both behind their own NAT, that are trying to connect. As the NAT of neither machine can correctly route any incoming packets from the other, a connection cannot be established.

A NAT punch-through system is where both machines connect to a third party machine which, via some route, can connect to each other and establish the connection for them. In our network, as long as there's some possible route between all the peers that wish to connect then a network can be established. When a peer receives a message it forwards this message on to all connected peers except the one who sent it. All peers are only connected to one other peer that was already in the network at the time of connection, so there's no message duplication.

6.1.3 Reconnects

A weakness of this structure is that it can be vulnerable to disconnects. If the topology of the network happens to have formed a tree, with one peer connecting the two halves of the network, then this peer is a major weak point. The same is true if the topology is a star, with a single peer connected to all nodes. If that peer disconnects then the network would be split into pieces.

To handle this problem we have an auto-reconnect between the disconnected pieces. Those peers that were connected to the now disconnected peer are aware of the other peers from which it has been severed thanks to the network state information described in Section 6.2.3. Each peer will attempt to connect to each of these until successful, reconnecting the network.

When peers connect to the network they are sent information about which peers they should attempt to connect to in the event of a network split. This removes the possibility of peers creating multiple connections between themselves, which would cause message relay loops in the network.

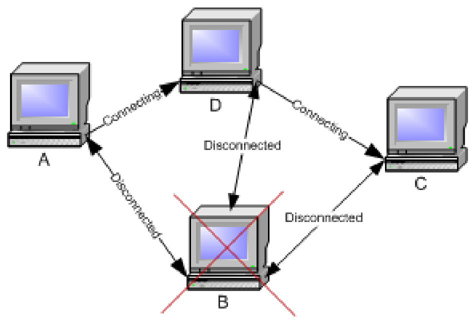


Figure 22: Peer B disconnects, peer A attempts to connect to D, peer D attempts to connect to C.

6.1.4 Ordering Streams and Priority

The network has optional packet ordering and delivery reliability, a feature provided by RakNet. By being optional, we can have very TCP like communication for messages that need it, while not having that overhead for those which don't. In addition to this, the ordering is managed using different sequence streams, so unrelated messages aren't in the same sequence.

Sequenced messages are labelled with a number which marks their position in the sequence stream. When sequenced messages arrive at their target peer they are discarded if a message with a later sequence number has already been processed. However, messages which are also marked as Ordered will wait for all messages with an earlier sequence number to be processed before they too are processed.

Message	Ordered	Sequenced	Reliable	Stream
Chat	✔	✔	✔	A
Draw	✔	✔	✔	B
Modify	✔	✔	✔	B
Delete	✔	✔	✔	B
Temp Draw	✔	✔	✔	B
Temp Modify	✗	✔	✗	C
Temp Delete	✔	✔	✔	D

Table 3: A matrix showing a selection of our message types and how our network treats them.

- Chat messages are ordered and reliable. Each message is received and processed in the correct order, and messages are not dropped. This is the expected functionality of an IM system.
- (Temp) Draw, (temp) delete and modify messages are ordered and reliable, but in a different stream to the chat messages. These messages do not depend on the chat messages arriving and vice versa. In addition, Temp Delete messages can be considered to be in their own stream.
- Temp modify messages are sequenced and unreliable. Out of order messages will be dropped, and lost messages won't be resent. These are high frequency, order dependent and unimportant. Once a message is missed it is out of date, if it is out of order it cannot be applied and they are of too high frequency but too little importance to justify the overhead required to ensure ordered arrival. We do not care if a temporary message is dropped as it is overridden by the next message and ultimately does not affect the result of the final event.

6.2 Network Implementation

The network consists of a singleton instance of a network library, which in turn contains an instance of RakNet. The network library provides an abstract layer between the rest of the application and RakNet. It handles session data, manages all connections, and performs the sending or forwarding of packets as required.

6.2.1 Subscribers

Objects which wish to handle packets can subscribe at runtime to the network as a packet receiver. When a new packet is received and it is not to be handled directly by our network object it is sent to each subscribed packet receiver in turn until one handles it. This system gives great extensibility and reduces the chance of bugs creeping in as the core network code doesn't need to be touched to add new message types, the extension can simply subscribe.

6.2.2 Serialisation

To send objects across the network we serialise their data into a RakNet BitStream. A BitStream wraps a dynamic array of packed, compressed bits. It provides an alternative to defining custom structs for packet data and handles compression and endian swapping automatically. The compression used is fast and simple, designed to give a space saving without being computationally expensive[17].

The algorithm is as follows:

1. Is the upper half of the input bits all 0's (1's for unsigned types)?
   TRUE: Write a 1.
   FALSE: Write a 0 followed by the upper half.

2. Repeat 1 on the lower half, until we are at half a byte.

Serialisation into a BitStream is as simple as calling `BitStream::Write` and passing the data to be serialised. Extracting the data from a BitStream consists of calling `BitStream::Read` in the same order as it was written, passing the variable to read the data into. Once an object is serialised into a BitStream it is passed to the network object with information on how it is to be sent (ordering and reliability). The network object then passes it to RakNet, where each connected peer dispatches it.

6.2.3 Sessions

Data on the currently connected peers in the network is stored in a Session object. Each peer in the session has all its key data held in a `Person` object. `Person` objects contain a numeric id, a username, an ip address and timezone information. In addition to this, each peer has a Person object describing itself and contains an additional array of all directly connected peers.

The numeric id is used to specify the vector index in a timestamp (see Section 4) for this peer. The username is used purely for gui display purposes and the ip address is used when a reconnect is required. Finally, the time zone information is used so that any received time information can be converted into local time.

6.2.4 Authentication and Compatibility

When a new peer connects to the network the first thing it makes is an authentication request. This request contains a desired username, the password for the session and the network version of the connecting client. To create this request an instance of a helper class called `MSG_PEER_AUTHENTICATE` is made. The desired data is passed to this new object which is then serialised and sent across the network. When this message is received it is deserlialised and the data processed.

During the processing of the authentication request the following actions are taken. In all cases if the action fails then an appropriate rejection message is sent back.

1. The password is checked.
2. Network compatibility is checked. The application contains an internal version number and each time a compatibility changing break is made this is incremented.
3. Username conflict is checked. This compares the requested username with a list of all known usernames.

6.2.5 Assigning of Unique ID

If these initial tests are all passed then a unique ID needs to be selected. Because multiple peers may be connecting at any given time to any connected peer in the network we cannot decide what this ID will be without consensus from all peers. The problem of arriving at such a consensus for a single result amongst multiple unreliable participants was discussed by Leslie Lamport[23] and has been solved in the family of algorithms known as Paxos. Our modified Paxos approach takes into consideration both our specific needs and the data available to us. We believe this implementation provides a robust and high performance method of finding the unique ID, as well as providing an extra guarantee that usernames in the session are unique.

Each action taken is described by a role in the protocol:

- Acceptor - These act as the approvers of each request. For any request to succeed, all Acceptors must approve, or if they are also a Proposer, be overruled.
- Proposer - The peer that handles the authentication request. It co-ordinates with the Acceptors and resolves any conflicts that occur.
- Client - The connecting peer that the Proposer is acting on the behalf of.

Condition. *The following must hold;*

- *The session creator has the id of 0.*
- *Each peer knows of a highest ID, N, which is the same value across all peers when no proposals are taking place.*

Acceptors are selected as all peers currently connected in the network. Once a proposal is made, any new peers connected to the network are not considered as Acceptors for this proposal.

The process of proposition can be described by the following steps:

1. The Proposer selects an ID of 'N+1' to propose and sets this as the new N value. It sends this and the proposed username to all Acceptors.
2. (a) Each Acceptor updates its N value, then checks that the proposed username is unique, rejecting with `BAD_USERNAME` if not.
   (b) Each Acceptor which is also a current Proposer checks that it isn't currently proposing the same ID, rejecting with `ALSO_PROPOSING` if so.

    (c) Each remaining Acceptor approves.

3. (a) If the Proposer has received a `BAD_USERNAME` response then the proposal has failed and the Client is notified of the reason.
   (b) If the Proposer has received no `ALSO_PROPOSING` responses then the proposal has been accepted and the Client is notified.
   (c) If the Proposer has received any `ALSO_PROPOSING` responses then it checks the ID of each conflicting Proposer. If any ID is lower than its own then the proposal has failed. The Proposer starts a new negotiation at Step 1.
   (d) If the Proposer has the lowest ID out of all conflicting Proposers then it has won the conflict resolution and overrules those other Proposers, accepting the proposal. The Client is then notified.

Once a proposal has been accepted the Proposer completes the authentication process. This involves informing the Client of its new ID, along with data on all peers in the network, calling any callbacks for processing and dispatching messages to all other peers notifying them of the new peer. The new peer message also acts as a final notification to all peers in the network that the proposal has been accepted, ensuring that all peers that connected during the proposal have an up-to-date max id N.

If the Acceptor disconnects from the network during a proposition the response of this Acceptor is decided by whether or not it is a leaf peer. A peer is a 'leaf peer' if it has only one connection to another peer, else it is a branch peer. Dependant on this if the Acceptor is:

- A leaf peer: The response is treated as accepted.
- A branch peer: The response is treated as rejected.

In all cases the Client receives appropriate feedback as to why it has or has not been able to connect to the session. Other Paxos based algorithms may be more likely to create a connection, but at a communication latency and system complexity which would make this less desirable than an informative failure message in the rare event of network disruption occuring. Our method provides what we believe is the correct balance between response time and connection success.

7 Evaluation

7.1 Comparison With Initial Requirements

	Requirement	Completion
Key	Collaborative Drawing	✔
	Distributed	✔
	Text Chat	✔
	Freeform Drawing	✔
	Object Repositioning	✔
	Vector Resizing	✔
	Text Labels	✔
Advanced	Logging	✔
	Version control	✔
	Joining of a session after it has started	✔
	Save and resume sessions	✔
	Click and drag-to-size polygon palette	✔
	Permissions on drawing	✔
	Export diagram as image	✔
	Audio chat	✗
	Tabbed canvases	✗
	Layered canvas	✔
	Auto-correction of lines	✗
	Shape Recognition	✗
Additional	Undo/Redo	✔
	Live Drawing	✔

Table 4: Comparison of initial requirements against completed project, ordered by importance to the project.

7.1.1 Completed Requirements

By the end of our project's development we fulfilled all the key requirements as laid out in Section 1.2.1. In doing so we have produced an application which meets the original specification for Tabula. We are satisfied with the implementation of our key requirements, including freeform drawing, text chat, text labels and simultaneous drawing over a distributed system. We believe that these operations are implemented in a clean manner and are easily accessible to the end user.

We were again satisfied with the advanced requirements which were successfully implemented. Saving and reloading sessions works smoothly in a maintainable manner; we believe through the use of XML that the saved logs should be future proof and clear to anyone attempting to reuse our project or logging systems. The ability to reload a session and continue with it in a distributed manner is also a feature which we are pleased to have implemented and see this as being of vast use on large scale projects. Users are also able to join conversations part way through and be updated to the current status of the canvas. This is another feature that we are happy to see completed as we believe it provides many benefits to an end user. Simpler tasks such as exporting the image and setting permissions on the canvas work sufficiently.

In comparison to Windows Live Messenger, Windows Journal and iScribble, as discussed earlier in the report in Section 6.2.3, our application does fill the gaps we identified between these various applications. Table 1 shows the rich feature set we have been able to develop by focussing on the problem of drawing within the context of distributed collaboration rather than as an art form or attachment to an Instant Messenger client.

7.1.2 Dropped Requirements

During development we re-evaluated our advanced requirements and selected several which we dropped from development due to time constraints, namely audio chat, shape and line recognition and tabbed canvases. These features, apart from audio chat, were seen as having the least impact on functionality of our project compared to time required to implement them. We would like to see these features implemented in a later version of the project and believe that through the design patterns used in our project they would be relatively simple extensions.

Shape and line recognition were seen as redundant when standard shapes and a line tool were available from our palette and would only provide benefits to users of Tablet PCs. We have built the freeform drawing context to include a preprocessor class for the recorded coordinates. Code exists to check whether a preprocessor has been assigned and will execute it, passing the point coordinates so the preprocessor can handle these appropriately. An algorithm for line and shape detection can easily be implemented though this system and output can be redirected to the correct shape creation classes.

Audio chat is the dropped feature that we would most like to have seen make the final version of our project. We believe that it would have provided a more immersive experience to end users and would have been of great benefit to increasing productivity when using our project. At first glance adding voice chat appears to be a simple task, the Raknet framework supports VOIP (Section 2.2.4), however we would have liked to include audio chat in our logging system and it was deemed that this would place too much development overhead on a single advanced feature.

Our investigations on adding audio chat identified a few areas where there would be some major work needed. The RakNet VOIP plugin has two important dependencies, Speex for audio compression and Portaudio for microphone input. Both of these dependencies were quite out of date and broken when compiles were attempted. Updating both of these would have required many changes to the VOIP plugin due to the extent of API compatibility breakage. However, this would be a very feasible task for a future expansion of the project.

Adding logging to the audio is a more challenging task, but possible due to the extensibility of our event system. A voice event could be added which would contain speex compressed audio frames. These frames would be taken in fast snapshots so that audio is fluid but also timestamped for accurate playback.

Tabbed canvases were also a feature that initially seemed useful, however as the project progressed we realised that implementing this as an advanced requirement would require the redesign of core sections of our project. We would need to provide a log per canvas, provide a Singleton container of these logs, add a vector to the `Event` class to reference these canvases and, of course, update the GUI to provide tabs. We feel out of any feature tabbed canvases are a small loss as they can be supported by multiple application instances running on different ports. Many other applications have added tabbed support in later releases, including Internet Explorer which only gained tabs in version 7[6], simply offering the ability to run multiple instances instead.

7.1.3 Additional Features

During the development of Tabula we did implement several alternative features to the dropped requirements. These arose through further thought, along with testing of our application which revealed features which we believe added significant improvements to the requirements outlined above. We developed these instead of the dropped requirements as they either required less time to implement or had a higher cost/benefit to the application.

The feature we are most impressed with is “Live Drawing” as it allows distributed users to see what is being drawn as it occurs. This feature is enabled via the “Fast Connection” option as it does increase the volume of data transfer. This is at its highest when freeform drawing is used where it can approach 8kb/sec per live drawing, however for standard tool palette shapes and move actions this is significantly smaller.

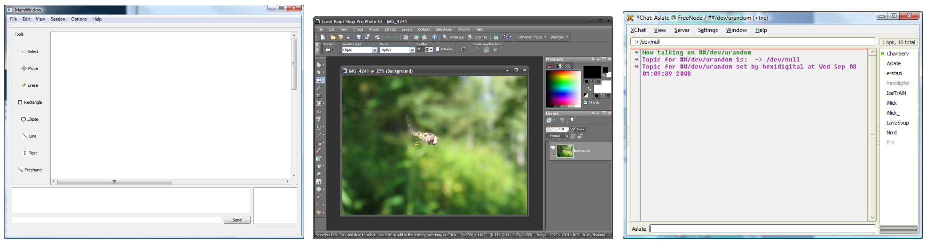
We also implemented an Undo/Redo command. This was a feature that naturally came from our logging system and simply requires moving forwards or backwards through appropriate log actions, for example, you can’t undo a chat event. This provides a highly useful and commonly expected feature and required very little overhead to implement.

7.2 Usability

7.2.1 GUI

Our GUI provides all the basic functionality that Tabula needs to meet our requirements. It has a clear separation between the drawing area and text chat, the two main features that our application deals with.

Tabula follows conventions as laid down by other applications that share parts of its functionality. We follow graphics applications with respect to drawing functionality. The use of a tool palette is common practice in graphics applications, as can be seen in Figure 23(b) and we ensure it provides adequate identification of the tools available. This is achieved through appropriate use of iconography, text labels and use of real world analogies (e.g. the use of a pencil eraser for the erase tool). The chat element of our system closely follow IRC conventions: a large message history, a side bar with current participants and an entry dialog along the bottom as shown in Figure 23(c).



```
* Now talking on ##/dev/urandom
* Topic for ##/dev/urandom is:  -> /dev/null
* Topic for ##/dev/urandom set by hexidigital at Wed Sep 03
  01:09:39 2008
```

(a) GUI Final (b) Paint Shop Pro (c) XChat

Figure 23: Comparison of Tabula GUI with the slightly cooler Paint Shop Pro X2 and an IRC client.

We do believe that our GUI, although functional, is relatively bland and simplistic for a graphics based application. Although it was our intention to keep the user interface clear and simple, as these types of application can get cluttered easily, we may have neglected user friendliness. The addition of a graphic designer to the group, or anyone with design experience, would have provided for a more exciting and evocative GUI. More time would have been spent producing a more refined GUI, however we repeatedly had issues with producing GUIs in Qt, as further outlined in Section 7.4.2.

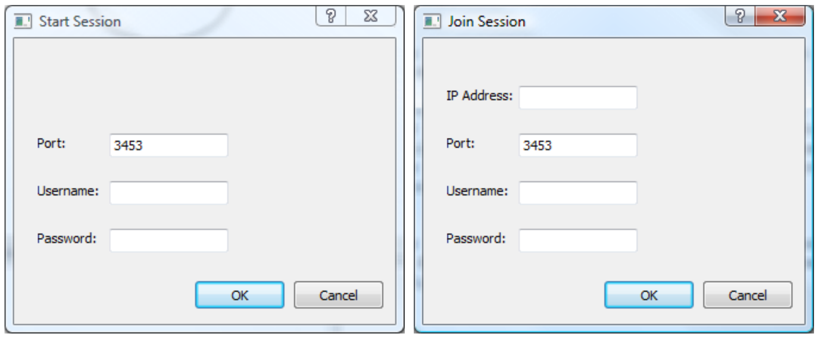
There are several options that can be triggered from within our GUI that could be combined into a much clearer options window. These would include the settings and connection speeds. This would also allow for better management of advanced and future features, with the introduction of a standardised options window.

We were also unable to get transparency working correctly on icons within the application, hence icons are filled with a gray or white background to reduce this effect (otherwise transparent areas are changed to a vibrant pink).

Although fulfilling our requirements, the GUI is limited in terms of extensibility. We have issues, as outlined above, affecting the ability to remodel the GUI directly. We also did not consider extending the GUI as part of our system design, instead choosing to focus efforts on providing extensibility within the actual application. However, through the course of building Tabula we have thought of several ways in which the application can be extended and now realise that extending GUI functionality is a requirement for several of these improvements. We discuss how we would improve the GUI implementation to facilitate this in Section 8.4.6.

7.2.2 Learning Curve

Tabula has a fairly low learning curve for the standard user. We expect users to be familiar with both our graphics and chat interfaces due to the attention taken to ensure these follow existing conventions, thus allowing for fast out-of-the-box functionality. There are a couple more advanced features which will



Port: 3453
Username:
Password:

IP Address:
Port: 3453
Username:
Password:

(a) Start Session (b) Join Session

Figure 24: The start and join session dialog boxes. Although perfectly acceptable for an advanced user require knowledge of certain terms and information.

require some learning before the user will be fully comfortable with their use.

The start and join session dialogs may be slightly confusing, as shown in Figure 24. These require the user to know about 'Ports' and 'IP Addresses'. We provide clear documentation of how to connect and join a session within the user manual to mitigate the effect this has on Tabula's adoption with novice users. We discuss how we wish to improve this in Section 8.4.6.

The most complicated part of our project is the versioning system, which we believe has a higher barrier to entry compared to our other features. We expect this due to the nature of the feature and believe that the users that would wish to make use of this feature should have a certain level of familiarity to version systems, thus we expect them to be able to pick up our implementation fairly quickly. Novice users would have to read about using this in our user manual.

7.3 Architecture & Design

Our project inherently has a strong Software Engineering bias, relative to mathematical or algorithmic content. We therefore prioritised system architecture and design throughout the development cycle, with large quantities of time spent developing the underlying system. We believe our project has a successful and strong underlying architecture because of this, ensuring an easy to maintain source base with clear modularity providing for future extensibility.

The quality of our design was fundamental to the success of our project providing us with the ability for rapid feature implementation near the end of the development process. The underlying architecture took a while to both finalise and implement. However once completed, it provided the foundation for rapid feature implementation, to illustrate this point, the completion of 50% of the requirements occurred in the short space of a week after spending months on design and architecture. In addition, the extension of the application in numerous ways (e.g. adding colour to objects) would be quick to implement because of the beautiful patterns implemented.

We found the isolation of different components helped as we made modifications to the design. In particular, the final decision on how to describe events took a long time to arrive at, during which the implementation was very volatile. Despite the fact that the log subsystem changed several times the other subsystems remained relatively stable, a sign of relatively low **coupling** between the different components. There is a level of coupling between components, namely because the Board subsystem is forced to know about events. `Board` depends on `Log` for `Event` objects, despite the fact that it should only need to know about graphical items.

One solution to this might be to place an additional layer of abstraction between the board and the log, essentially fabricating a class which knows about both events and graphics. In this way if we changed the implementation of events, the board would not be affected at all. The drawback would be that the board system would comprise the `Board` and the abstraction class, similarly the Log would comprise both of itself and the abstraction class. Essentially if either the board or log changed, the abstraction class would change too. However the Board and the Log would now remain closed for modification if either of them changed, and the abstraction class would only be a slight extension of each system essentially encapsulating the parts that change from each half of those subsystems system.

We reduced coupling between controllers by having a call back system. We applied the expert principle wherever possible, for example objects that need to be serialised serialise themselves. This way if their implementation is modified, those changes are confined to the one class.

7.3.1 Software Engineering Patterns

The use of MVC was highly effective. This allowed our models to be transformed into those that Qt's pre-defined views would accept simply by inheriting Qt's `QAbstractModel` class. This allowed us to quickly add in views that offered the functionality we required to fulfil the requirements, and would allow any future developers to change these views for others with little or no code modification.

The use of the Strategy Pattern for changing the tool at runtime is amazingly extensible; especially when we consider the alternative, a set of `IF` statements, and the lack of extensibility this offers. This would require the processing of `mouseDown` events via nested `IF` statements, reaching at least 3 levels each with 5 alternative `IF`s, a total of 15 code blocks. (tool, (mousedown, mousemove, mouserelease),itemundermouse) and then 1 of these 15 code blocks for each tool. The result would be a section of code reaching into the tens of thousands with enough tools. Our architecture confines these options to a class, with only one class needing to be added per tool.

We currently offer extensibility to the programmer by placing pointers to objects which inherit from a common interface or abstract class in key places throughout the program. We can then simply check if these pointers are assigned. The main example of this is our preprocessor, which could be used to hook in a handwriting recognition system by allowing the drawing co-ordinates to be passed to an appropriate algorithm. However, it would be nice to have been able to offer extensibility to programmers without the need to modify the application through the use of a plugin architecture.

We have previously discussed several alternatives to our chosen design throughout Section 3.

7.3.2 Tug of War

Our system is concurrent and allows for multiple users to simultaneously move objects on the canvas. Because of this there are inherently race conditions in the system:

1. **User 1:** Click shape
2. **User 1:** Start to drag shape
3. **User 2:** Click shape
4. **User 2:** Start to drag shape to different location
5. **User 1:** Release shape
6. **User 2:** Release shape

The expected result is that whoever releases last gets the final say in the object's position. Indeed, this is the behaviour experienced during 'Slow Connection' mode.

Inadvertently, we stumbled across a solution to the problem whilst trying to make the application more visually compelling. In 'Fast Connection' mode we implemented the movement system by emitting temporary `Draw` objects so that the shape on User 2's canvas starts to move as soon as User 1 moves it. These are implemented by sending the difference from the shape's current position as opposed to the coordinates of the new position. This results in what we have dubbed 'Tug of War'. Two users pulling an object in different directions is analogous to a pair of forces acting on an object, the object moves in the direction of the vector sum of all movement actions. We found this to be an interesting quirk of our system, however we do feel that this won't be an issue as if User 2 sees that User 1 is already moving the object, the tendency will be to back off.

7.4 Choice of Languages & Tools

7.4.1 C++

We chose a combination of C++, Qt and Raknet early on in the development process. In discovering the functionality offered to us through Qt and Raknet, which is a C++ only framework, our language selection was made for us. We were fairly happy with the choice of language as the group had a good knowledge of C++ and prior experience with both of these frameworks, allowing for rapid development throughout the project. We also had two experts in using these tools, Dan who has significant experience of Qt and Mike who has years of high quality C++ development.

In reflection we believe that Java, through its built in ability to serialize objects, would have resulted in easier development of passing objects over the network. The use of C++ meant we had to spend a large part of development solving the problems of pointers during serialization of graphics objects, this was in fact the single largest problem faced during development. However we also believe that the overhead of finding and mastering the appropriate replacements for Qt and Raknet would have exceeded the benefits provided by simplified serialisation.

7.4.2 Qt

Qt supported our implementation of MVC, this provided us with vast flexibility in our use of Qt's components. We were able to develop mock ups and prototypes quickly and later modify them into a richer system. This was specifically useful in the development of the chat system which we were later able to customise with formatted text by simply swapping the view, leaving the controller and model unchanged. Qt also provided us with many additional libraries such as a full XML parser, a feature that we found useful when approaching offline logging systems (as discussed in Section 3.2.2). This helped reduce program complexity, avoiding the need to overcome dependencies when using an external XML parser.

We did have several issues with using Qt for our GUI. We found that manual creation of a GUI through code was a highly time consuming and fiddly area, so we switched to using QtDesigner which is a GUI creator for Qt. This software is still in Beta and again was time consuming to use and highly unstable. Due to this GUI design and implementation took around 14 hours total, a remarkable amount of time for such a simplistic interface. Editing the GUI at a later date required a complicated merger procedure between QtDesigner and existing code held in Visual Studio, as well as many problems attempting to modify the GUI itself within QtDesigner. Modifying the GUI once between our initial prototype and final GUI took a total of 4 hours! If you compare the two revisions of our GUI between Figures 17 and 18 this is shocking for the minor modification required. In modifying the GUI in this way and merging the new GUI code with our codebase we also re-introduced several bugs such as the read only properties of the chat history.

We would have preferred to use C# and Windows Forms as an alternative framework and GUI kit as support for this is integrated into Visual Studio and would have reduced time spent on the GUI drastically. However due to our requirement to have a cross platform application C# was not available to us. The mock up GUI for our application shown in Figure 25 took a total of 10 minutes to produce. To hook this GUI into the application itself is also far easier than Qt, integration with Visual Studio allows you to simply double-click a button to implement `onClick` behaviour. Modifying properties in C# is also easier as there is a standard properties dialog with all related properties for a component. This means we do not have to spend time trawling through documentation to enable to disable features. We believe if we were able to use C# our GUI development time would not exceed 2 hours to produce a final

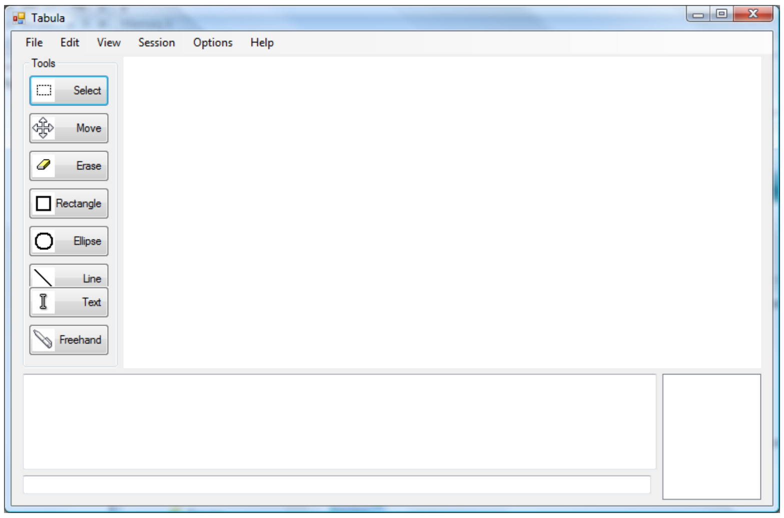


Figure 25: A Windows Forms based GUI

version.

7.4.3 Jam

Although Qt comes with QMake - a custom make replacement, we found it hard to use mostly due to it being inflexible. We needed a way to be able to quickly integrate other libraries into our project without having to spend time dealing with several methods of compiling. In addition to this we required a way to easily update the Visual C++ project files so that there was a consistent, working set for all developers to use.

Mike had these requirements in the past and was experienced in using the Perforce Jam[2] make replacement along with the many scripts for cross-platform project configuration and VC++ project file generation available from the Crystal Space[1] project. Using these we were able to very quickly set up our build system for all platforms, then adding support for automatic MOC file creation at compile time for linux and mac, which is the only advantage QMake would have had. Unfortunately there was no auto-creation for Visual Studio, which the majority of our developers were using for an IDE.

7.4.4 Raknet

RakNet provided an excellent network layer for our program and presented no noteworthy problems. The BitStream class provided by RakNet helped simplify our serialisation implementation so we could spend time on design rather than trying to get it to work. Without it we would have needed to spend many more hours manually implementing the same functionality ourselves, not including debugging time! That could have been a serious obstacle to the success of this project.

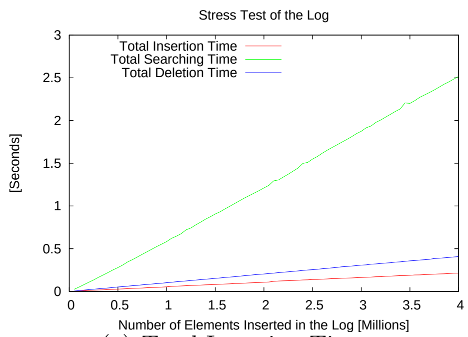
The performance of RakNet met our initial requirements easily, allowing us to implement more ambitious features such as live drawing without needing to worry about whether or not the program would have usability issues due to the network. Likewise, there were no stability problems to report and integration into our application was extremely simple.

Overall RakNet has proven itself as a good choice of network library and we would definitely use it in future if the opportunity arises.

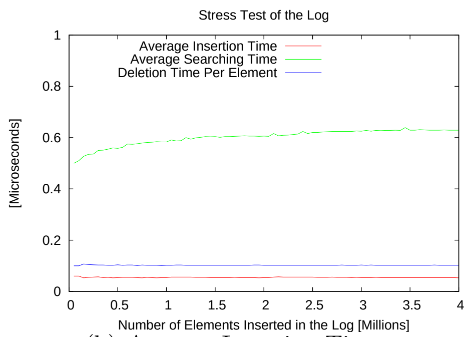
7.5 Benchmarks

7.5.1 Performance of the Log

Though the network is the bottleneck of the system, we analysed the impact of the size of the log onto inserting, searching and clearing time. To evaluate the performance of the log, we inserted different amounts of `Events`, searched through them and cleared the log again. The number of `Events` varied from 50,000 to 4,000,000.



(a) Total Insertion Times.



(b) Average Insertion Times.

To prevent inaccurate measurements, we measured the time for a batch of insertions resp. searches in total, since one operation itself is very fast. In Figure 26(a) you can see how long insertion of x `Events` takes in total (red). You can also see how long it takes to search for every of those inserted `Events` in total (green). Finally you can see how long it takes the log to deallocate every `Event` inserted (blue).

In Figure 26(b) all measurements have been divided by the number of operations done, which is x. This is to show how long it takes to do one operation on average on logs of different sizes.

The lines in figure 26(a) are supposed to increase at least linearly as the number of operation increases linearly, whereas Figure 26(b) is hinting at the time complexity of one operation.

Since we are only inserting fresh events, they will be appended to the list, which takes a constant amount of time. Inserting relatively fresh events is the average case for normal collaboration, joining sessions (receiving a Live Log via network) and resuming a session (loading an XML file).

In theory an STL vector takes $\log x$ allocations until it grows to the size of x. However, in practice that time needed for allocations does not seem to influence the average insertion time. Searching for events shows an expected $O(\log x)$ graph, since we are using binary search.

The clearing of the log does include deallocating the bag of events as well as the deallocation of every event. This results in constant time complexity per event stored in the log.

7.5.2 Performance of the Network

The network is a key performance point in our system, as high traffic usage or slow response times would heavily impact usability. To evaluate the network performance we used packet analyzers to monitor the traffic and measured latency using tools built in to RakNet.

Network traffic usage with live drawing averaged 4KB/s per user, peaking at 8KB/s per user. Without live drawing the traffic peaked below 500B/s per user. This suggests that our 'low bandwidth' mode which disables live drawing would accommodate users in areas of poor connectivity with ease. The topology of the network has a great effect on the specific bandwidth requirements of each user. In a star topology, one user will have a much higher load than the others, yet the average across the network will stay the same. It would be worth investigating a future addition to the network which automatically shapes the network to achieve the most optimal topology.

The packet size distribution shows that the majority of our packets are quite small, with a noticeable lack of packets in the >256byte range. We would conclude from this that the network is well suited for slower (<=56Kbps) connections which cannot handle a large number of big packets. We believe the few large packets are created from freeform drawing objects and could be reduced in frequency even further with more optimisations to how these are handled, such as applying a preprocessor filter to find the optimum number of points in a freeform path.

Packet Size (bytes)	Bytes	Packets
<=64	448	7
65-127	174,215	1,911
128-255	508,486	2,529
256-511	67,574	242
512-1023	7,354	11
1024-1517	23,686	17
>=1518	54,850	37
Total	836,602	4754

Table 5: Sample packet distribution in a draw session in 'Fast Connection' mode.

Latency tests produced expected results, with no noticeable overhead inside the network library compared with other applications used to monitor latency such as Ping[3].

7.6 Statistics

Section	Lines
apps	3600
include	500
libs/graphics	3200
libs/log	2800
libs/network	1300
libs/session	200
Total	11600

Table 6: A table showing a breakdown of lines of code written, to the nearest 100.

8 Conclusions

8.1 Time Management

The most important conclusion from the development of Tabula was that of time management. This is not limited to overall time management for the project but time management of individuals within a group. When setting out to develop Tabula we had a fairly sound timetable for completion, as demonstrated in reports one and two. We did not, however, properly take into account the members' individual timetables, such as those applying for internships as part of the MEng course.

Our team leader set out to arrange his placement extremely early to get ahead of the application rush, resulting in minor delays in initial planning and design. A second member of the group then began his search once the team leader was finished, this resulted in an inability to code for a total of just under 2 working weeks due to interviews and exams. A third member then had a work placement over the Christmas break resulting in delays in the compilation of this final report. We now realise that if we timetabled these as a group we may have been able to minimise time lost, getting coders to apply during design stages and designers to apply later.

We also had issues with estimating development times. We did not foresee the large problems caused by sending graphics objects over a network in C++ and just how much development time would be dedicated to solving this fundamental requirement. Alternately the development speed for several other sections was vastly shorter than estimated due to coder experience. The estimates were perfectly reasonable for these sections at the offset however we did not have accurately identified all factors affecting development time.

Overall we have learnt to respect time management and estimation far more then we had originally. Specifically, we found we were in direct agreement with 'The Mythical Man-Month', that man-months do not exist and men and months are not interchangable[21]. Although forewarned in the Software Engineering lectures, when we found that deadlines were slipping we attempted to shift manpower from documentation to development. As predicted, more time was spent in training them than was saved in approaching the deadline.

With our leader having looked at the book, we realised we were about to go down the vicious circle that is adding more men, training, more time used, pushing back deadlines. We quickly withdrew the extra man power and instead negotiated alternative ways of implementing certain features. For example, we originally envisaged that our resize feature would follow the convensions in such products as Microsoft Visio where an object can be resized intuitivly by it's handles, however we estimated that we did not have sufficint time to implement this. Since it was a key requirement we opted instead for a dialog box which still allowed the user to resize, but not interact directly with the object. This was cleared with our supervisor beforehand and was an effective way to solve the Man-Month problem of overshooting deadlines.

8.2 Software Engineering Patterns

As mentioned throughout our evaluation and future work, software engineering patterns were highly effective throughout development of Tabula. This has been the first major project where we have been able to apply several patterns and it is very nice to see the transition from just being 'a course taught in the second year' to a highly useful tool in a real world situation.

Of particular benefit were the strategy and bridge patterns which we have not implemented before. The strategy pattern was very powerful, we used it to allow for behaviour to be interchanged at runtime for various tools. The bridge pattern meant we were able to avoid a class explosion when it came to defining behaviour of tools for different shapes. These two, along with MVC of which the group had prior experience, are patterns that we would happily employ in future projects and can foresee them simplifying future development.

8.3 Use of Frameworks

We found that frameworks provided us with many benefits throughout development of Tabula, of particular note we have RakNet's networking functionality which sped up development of the distributed section of our project. Both frameworks performed well and provided the ability to get the project off the ground running, however we did hit walls later on in application development, namely with specific parts of the Qt GUI.

In this application we were restricted to having a cross platform application, resulting from this restriction Qt was the best framework available to us (as we discussed in Section 2.1.5). If we were developing a Windows application then we would have opted for a combination of Visual C++ or Visual C# as these both provide integration with the Windows Forms GUI. Windows Forms is a highly robust GUI development kit which makes the development of standard GUIs incredibly simple.

Ultimately, frameworks are a huge benefit to any project. Their ability to provide many features out-of-the-box is a huge benefit to any developer and we are glad that we used our combination of Qt and RakNet, even if we had to work through their flaws.

8.4 Future Work

There are many additional features that would add to the functionality of our project, along with the advanced requirements which we were unable to implement from Table 4.

8.4.1 Drawing Functionality

There are several improvements we would like to have made to our drawing functionality. The biggest of these which we believe is fairly core to a doodling application is the addition of a colour palette for line, foreground and background colours, along with the ability to change these at a later date.

Importing images onto a canvas would also improve the user experience, allowing them to import already created graphics and further annotate them. Ultimately we see this being implemented in a drag and drop manner, creating a new `Image` implementation of our `DGraphicsItem` class, which can then be manipulated using the standard tools.

We would also like to increase the functionality of the permissions system to be more advanced, closer to that seen in Unix or Windows file permissions with increased granularity and dynamic permission modification. In a similar vein an IRC system of operator permissions may be useful within chat, this could allow a figurehead such as a lecturer to grant and block various users from contributing to either the chat or drawing.

Several applications that support freeform drawing support line smoothing and anti-aliasing, reducing the jagged finish of lines produced through tablet pen or mouse movement. This, along with handwriting recognition, could be implemented in a similar manner to shape detection as outlined in Section 7.1.2.

8.4.2 Chat

The chat system could be adjusted to use a variety of different IM systems in a plug-in manner, allowing the system to be used over Google Talk, MSN Messenger or AIM networks and including the user's buddy lists from these networks. This would improve the overall user experience, increasing the friendliness to new users and bringing the product to a more mainstream audience. The contacts system itself could then be modified to include avatars, display names, groups and user status. We support the ability to do this through our use of the `Q`.

8.4.3 How to Add an Operation

We shall now outline several examples of operations which could be future expansions for the project, explaining the various points in which you can hook into the system. We believe our architecture makes this fairly simple to implement.

To add the ability to colour a shape Qt already supports colouring of objects via the `QBrush` and `QPen` classes, so we simply have to propogate these changes throughout network. All we have to do is implement an additional private member variable which describes the colour in some way, typically as an RGB value, along with a pair of `set()` and `get()` public methods to access it. These would be implemented in the iDesc interface and inherited by all concrete descriptors.

If Qt were to implement a new basic shape, such as `QTriangleItem` implementing a triangle, we would only have to implement 2 new classes. Firstly `DTriangleItem` which would extend `QTriangleItem` for reasons described in Section 3.4.4 and then a descriptor class to describe its dimensions.

To build custom shapes we can make use of the `QPath` class; we already use this implement freehand drawing by passing a series of points. `QPath` contains advanced methods, such as `lineTo()` and `arcTo()`, which allow you to draw very complex shapes. In theory it would be possible to create a custom object by invoking such methods, in which case all we need a way of communicating and executing these instructions.

We already use Qt's XML library for creating a permanent log in Section 3.2.2. It would be trivial to describe custom shapes in XML and have a class of processors which parse the XML and instantiate a QPath object from it. The descriptor would consist of a String payload. The BoardController would be responsible for calling the classes required to parse the string payload from the descriptor.

We now outline how we can effectively parse XML descriptions of multiple custom objects with reference to Figure 26: You have a master processor, the purpose of the master processor is to parse the opening of tag of the XML document which should indicate what 'type' of custom shape we are parsing. It should then delegate the processing activity of the shape to the appropriate slave processor. When the master processor parses the opening tag, it will return a string to indicate the type of shape. There is nothing inherent about a string which we can use in OOP to architecturally switch processors, so it is tempting to use a series of IF statements, this makes extensibility difficult, so we propose a mapping of Strings to Slave Processor pointers via a StringToProcessorMap class which allows the master processor to lookup a pointer to the processor which should handle the document using the string returned from the opening tag. Future custom shapes will simply require their own processor to handle the drawing.

Each slave should instantiate a QPath item, and call the appropriate methods as outlined in the xml. For example, the xml instructions below would cause the Master to select the hexagon processor and the hexagon processor would execute the instruction lineto(0,0).

```
<shape type="hexagon">
  <instruction type="lineto">
    <parmater value="0" />
    <parmater value="0" />
  </instruction>
</shape>
```

This system is very extensible as any number of custom shapes can be described using the single XMLCustomShape. Any design of shape is possible (within the limits of the canvas), and shapes can be as complicated as the designer is willing to make them.

The drawbacks to this design is that the descriptions for these objects would be costly to send and would at least require some compression before sending. This would result in additional waiting time for such graphical items to appear on other participants' boards.

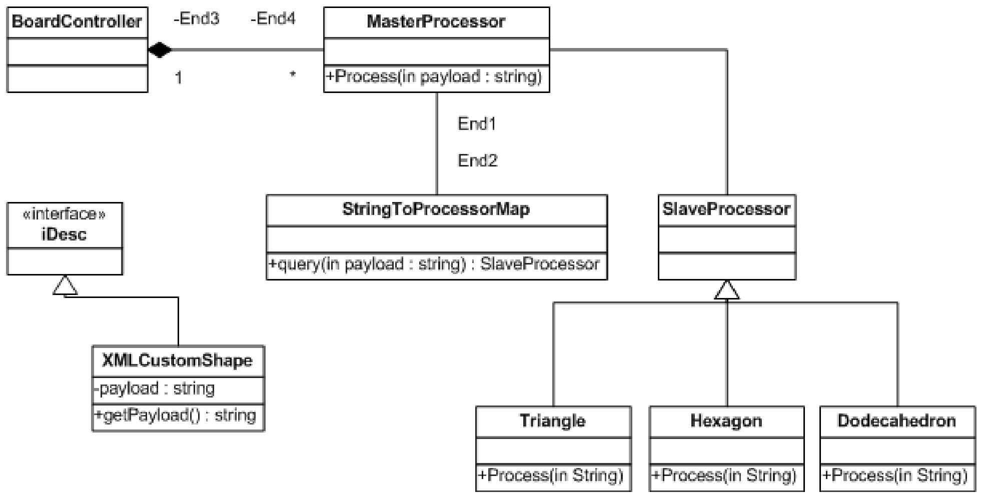


Figure 26: Class diagram showing how you might extend the existing system to process custom XML shapes.

8.4.4 Increased Collaboration

The main features that we would like to add would be to improve the collaboration experience. Windows Live Messenger includes features where you are not only able to send files, but mark several files as being shared. These files can then be opened and modified by other users and the owner is able to manage permissions and grant or deny access. We believe that the ability to share files in this manner, combined with the ability to doodle and converse about them increases the situations in which our project becomes useful.

The introduction of audio and video communications is another area in which we feel the project could increase collaboration. There are many implementation issues that need to be correctly identified before this can occur, such as talking over other users or how to display multiple video feeds at the same time. It is for these reasons that we believe this is an extension to our project rather than a feature that should be included in the initial release.

8.4.5 Custom Shapes and Graphics Packs

In choosing the QGraphicsPathItem for freehand drawing we also open up the system to the addition of custom shapes, described in XML. With a few modifications one could add an import entry to the toolbar to import shapes and have these imported shapes appear as a toolbox. Perhaps even have the notion of 'Graphics Packages' where users share their custom graphics items with each

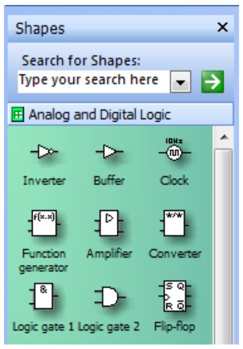


Figure 27: We envisage the ability to provide custom toolsets, similar to this implementation found in Microsoft Visio.

other when they join a session, resulting in a wide set of graphic items to play with.

One could have an electronics pack which contains common shapes used in electronic circuits such as logic gates. Contexts could be extended to provide analysis functionality, for example it could examine the electronic circuit and produce an input/output truth table or minimise the circuit diagram. This is quite a large jump from the original intention of the project, but the steps to integrate this would not be so large. The classes with access to the board information are already in place (contexts), all that is needed is for the programmer to handle their analysis of the points and objects on the board.

8.4.6 GUI Improvements

The toolbox currently has a limited number of buttons available, this could be extended by providing a carousel via some form of scrolling widget which would allow an unlimited number of buttons to be added to the carousel. This would then provide for a much better range of extensibility as more tools, custom shapes or the graphics packs from Section 8.4.5 could be made to use this system.

It might also be nice to allow the user to configure the GUI more, some systems such as the IDE we used to implement this software allow for toolboxes to be minimised, or hidden until the mouse touches the extremes of the window where they appear. perhaps a fullscreen mode for the canvas with a floating toolbar. like the one in MS paint would be an option for users who aren't multitasking with other applications.

Some users may not be familiar with the concepts of IP addresses and ports, and may find it difficult to connect. One could implement a way to save information about a session (IP and PORT) in a connection file, which you could then send to somebody. The file extension would be associated with the Tabula executable, and when double clicked would initiate the application and begin the connection process. This would then replace the dialog windows which we currently implement. One could also implement a method of looking up the user's external IP address as part of this process. We had difficulty here if behind a router, therefore only being able to return a local network address. We have also considered a lobby system, however this would require the introduction of well known servers which would host the lobby and would require reasonable modification to both the application and the network code as our P2P implementation does not report the session to a server.

Glossary

Bridge Pattern Decouple an abstraction from its implementation so that the two can vary independently. 36

coupling The degree to which software components depend on each other.. 59

deserialisation The activity of restoring the state of an object or a set of objects from their serialized form.. 46

Event An event is an action which is initiated by the user. In our implementation it is a composite class which describes the action that occurred, and by composition gives details about the action.. 44

expert principle Assign a responsibility to the class that has the information necessary to fulfill the responsibility. 24

Graphical User Interface (GUI) The part of a software application that the user sees and interacts with.. 13

Homomorphism A homomorphism in general is a weak homomorphism.. 37

- **Strong Homomorphism** A strong homomorphism is a homomorphism that maps relations not in an implied, but in an equivalent way, that is $a_1 <_A a_2 \Leftrightarrow h(a_1) <_B h(a_2)$, where A and B are structures with a relation $<$.. 39
- **Weak Homomorphism** A weak homomorphism is a structure-preserving map between two algebraic structures. The map preserves the functions and relations of the concerned structures, e.g. $a_1 <_A a_2 \Rightarrow h(a_1) <_B h(a_2)$, where A and B are structures with a $<$ relation.. 39

Internet Relay Chat (IRC) The IRC protocol was first implemented as a means for users on a BBS to chat amongst themselves.. 31

Meta Object Compiler (MOC) The Meta-Object Compiler, moc, is the program that handles Qt's C++ extensions. The moc tool reads a C++ header file. If it finds one or more class declarations that contain the Q_OBJECT macro, it produces a C++ source file containing the meta-object code for those classes. Among other things, meta-object code is required for the signals and slots mechanism, the run-time type information, and the dynamic property system.. 13

Model View Controller Pattern (MVC) A design pattern used to decouple the Model, the View and the Controller to increase flexibility and reuse.. 13

- **Controller** An object which defines the way the user interface reacts to user input.. 24
- **Model** The object used to hold the internal representation for the application object.. 24
- **View** The screen presentation of a model. 24

packet A sequence of binary data of restricted length wogether with addressing information sufficient to identify the source and destination computers.. 16

Partial Order By partial ordering we are talking about strict partial ordering which is a binary relation $<$ over a set which is irreflexive, antisymmetric and therefore transitive.. 47

peer-to-peer A network where all participants interact cooperatively as peers without any distinction between client and server processes or the computers that they run on..

peer A participant in a peer-to-peer network.. 37

serialisation The activity of flattening an object or a connected set of objects into a serial form that is suitable for storing on disk or transmitting in a message.. 46

Singleton Pattern Ensure a class only has one instance, and provide a global point of access to it.. 25

Strategy Pattern Define a family of algorithms, encapsulate each one, and make them interchangeable. Strategy lets the algorithm vary independently from clients that use it.. 28

Strict Weak Ordering A strict weak ordering of a set is irreflexive, asymmetric, transitive and transitive concerning equivalence (if x is incomparable with y, and y is incomparable with z, then x is incomparable with z).. 47

thread Entity which can be scheduled for concurrent execution with other threads within a process.. 13

Transmission Control Protocol (TCP) A connection-oriented protocol which provides reliable delivery of arbitrarily long sequences of bytes in the order sent by the sending process.. 16

User Datagram Protocol (UDP) A connectionless protocol offering no guarantee of delivery or order and no requirement for acknowledgements.. 16

Voice Over Internet Protocol (VOIP) VOIP protocols are designed for optimised transmission of voice data across a network.. 17

Wide Area Network (WAN) A network which carries messages at lower speeds between nodes that are often in different organiszations and may be separated by large distances. They may be located in different cities, countries or continents.. 48

widget Any object in memory which has a graphical representation on the screen and forms part of the Graphical User Interface.. 13

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