OXALIS: A DISTRUBUTED, EXTENSIBLE OPHTHALMIC IMAGE ANNOTATION SYSTEM

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ABSTRACT

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Currently, ophthalmic photographers and clinicians write reports detailing the location and types of disease visible in a patient's photograph. When colleagues wish to review the patient's case file, they must match the report with the image. This is both inefficient and inaccurate. As a solution to these problems, we present Oxalis, a distributed, extensible image annotation architecture, implemented in the Java programming language. Oxalis enables a user to: 1) display a digital image, 2), annotate the image with diagnoses and pathologies using a freeform drawing tool, 3) group images for comparison, and 4) assign images and groups to schematic templates for clarity. Images and annotations, as well as other records used by the system, are stored in a central database where they can be accessed by multiple users simultaneously, regardless of physical locality. The design of Oxalis enables developers to modify existing system components or add new ones, such as display capabilities for a new image format, without editing or recompiling the entire system. System components can elect to be notified when data records are created, modified, or removed, and can access the most current system data at any point. While Oxalis was designed for ophthalmic images, it represents a generic architecture for image annotation applications.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

Page

Page

1.0 INTRODUCTION

This chapter describes the motivation for designing Oxalis. We begin by detailing the problems with the current workflow of ophthalmic photographers, and then move on to discuss some currently-available image annotation systems.

1.1 Problem Statement

The resolution of digital photographic devices is increasing at a tremendous rate. While these devices are generally not yet capable of matching the resolution of 35mm or wide-format film, the resolution has increased to the point where a wide range of photographic professions can begin to replace film devices with digital ones.

One such profession is that of ophthalmic photographers. Ophthalmic photography is a highly-specialized form of medical imaging dedicated to the study and treatment of disorders of the eye [1]. The most common ophthalmic photographs are retinal (fundus) photographs, sometimes involving florescent dye (Florescein or Indocyanine Green angiography).

Formerly, these photographs were generally taken with specialized film cameras, and included with the patient's file. The clinicians would then comment on the pathologies apparent in the photograph in writing (or through the use of a tape recorder), describing the location and pathology as noted. When a clinician wished to review the file, s/he would have to match the original clinician's notes with the photograph, which results in both decreased efficiency and accuracy of reports and treatment. "Hard" records are also difficult to transport or share among multiple clinicians or facilities, resulting in delays in treatment time when specialists in different physical locations are involved.

Unfortunately, as digital devices replace ophthalmic photographers' film cameras, the "workflow" of diagnosis remains largely unchanged, with one minor exception: instead of developing the film pictures from retinal photographs, clinicians print out images from the digital camera on an ink jet or dye sublimation photo printer. Thereafter, the paper copy is included with the patient file (although the digital image is kept as a backup), and commented on as it was previously, resulting in the same inefficiency and inaccuracy.

To solve these problems, we have developed a software-based image annotation system. This system, called Oxalis, enables a user to display images from a number of file formats, select regions of interest (ROIs) on the images, and annotate the regions with a description. When another user selects the image, all previous annotations will be displayed as a semi-transparent overlay on the image, with the description of the annotation clearly labeled. Oxalis uses a central data warehouse (database) to store all of the image and annotation data. Clinicians use the Oxalis software to connect to the database, download images and annotations, and create new data in the system. Users can also create logical groupings of images, and assign images to schematic diagrams.

Image annotation systems have previously been developed. In the next section, we will describe several of these systems in brief. However, the vast majority of these systems use a file-based approach, relying on users to copy the image and annotation files to a web server's directory, or, in some cases, only allowing users to share annotated images through email.

The remainder of this paper is divided into three chapters. In the first chapter, we describe Oxalis from a user's perspective, detailing the functionality available to a clinician. In the second chapter, we describe the technical details that enable users to quickly and efficiently annotate images, and developers to modify or enhance Oxalis' core components. In the third chapter, we describe a possible future direction for Oxalis, allowing it to function in an "untrusted" environment, where the safety of developers' code and users' data must be guaranteed by the program itself.

1.2 Currently Used Systems

In this section, we present a brief review of some currently used image annotation solutions. We discuss the capabilities of these systems and their suitability for solving the problems of displaying, annotating, and sharing ophthalmic photographs.

1.2.1 Hardware Modules

Most medical imaging equipment, such as Computed Tomography (CT), Computed Radiography (CR) such as , Magnetic Resonance Imaging (MRI), Ultrasound, etc, provide a means to textually annotate a medical image with a graphic overlay, in order to describe items such as a tumor, a hemorrhage, etc. Siemens' "syngo" [2] CT device, GE Medical Systems' PathSpeed CR [3], and Agfa's ADC-IPD Viewer [4] are three examples of hardware modules that are capable of performing on-screen annotation. Most of these devices can also communicate with PACS (Picture Archiving and Communication System) or DICOM (Digital Image and Communications in Medicine) servers for storage and retrieval of images. However, the majority of these devices were designed to display and annotate images for their specialty. A clinician would be hard-pressed to annotate an ophthalmic image on a CT device, for example. The vast majority of these devices are entirely proprietary systems, which do not allow extensions to their capabilities by anyone but the machine's original manufacturer. This is both expensive and inefficient for end users, as an upgrade to the device's capabilities would require allowing a representative of the manufacturer to work on it, or, in the worst-case scenario, sending the device back to the manufacturer.

1.2.2 I^{2}CNet

I^{2}CNet (Image Indexing by Content Network) is a software-based image annotation solution designed by ICS-FORTH, and targeted for the medical imaging community. [5] It uses a distributed "client-server" architecture, employing an HTTP server and Java applets interacting with a central Java application to enable users to store annotations in a central repository. In addition, image annotations may be saved to the user's local machine (as ASCII text files), making them private to that user, and/or emailed to other users.

I^{2}CNet supports three different user roles: reader, author, and moderator. Roles are assigned on a per-server basis. The first two roles are fairly obvious: an "author" may create annotations, while a "reader" may only view them. A "moderator" is the administrator for an I^{2}CNet server. S/he is the only one capable of removing an annotation, or accepting an image and annotation for publication on the server.

This system is therefore "distributed", in that users can access images and annotations regardless of their physical locality, provided the annotations have been "shared" by the author, and approved for publication by the moderator. This greatly increases the amount of time required for data to be available to interested parties, and decreases the overall efficiency of the system.

While the modularity of I^{2}CNet's design, with a central server and multiple applets, would seem to indicate that extensions to the architecture may be possible, none of the publications ICS-FORTH has produced on the system makes any mention of the extensibility of the system, or the interface for doing so.

1.2.3 PAIS

PAIS, the Personal Annotated Image Server [6], is another software-based image annotation solution. It was developed by Dr. Bill Lober, at the University of Washington School of Medicine, and is targeted at medical educators.

PAIS allows a user to annotate an image with text pointers, which can be a pointer to another annotated image, save the annotations as an Image Markup Language (IML, an extension to XML) file, and view the annotated image in a web browser (using a Java applet). Once created, the IML file and image can be moved to a web-traversable directory, and accessed from a remote location. However, in order to annotate the image further, it must first be downloaded from the server, along with the previous annotation file.

PAIS is therefore distributed to the extent that an annotated image can be loaded and viewed remotely, and extensible to the extent that the author has published the source code on his web site. However, it suffers from some of the same shortcomings as I^{2}CNet, in that it is file-based, and images and annotations must be moved by the user to the correct file locations in order to be accessible by other users.

Generally, adding a new feature to PAIS would require a user to gain an understanding of the full source code, implement the new graphic elements to drive the new feature (in the original code), integrate the feature, and recompile the core. This would be inefficient for a developer, and would require users to find a way to synchronize changes from multiple source.

1.2.4 Show-and-Tell

Show-and-Tell, developed at the State University of New York at Buffalo, is an annotation engine that uses multimedia input and natural language processing to generate and find annotations in a semi-automated fashion.[7] Users of Show-and-Tell simultaneously point at appropriate image areas and speak into a microphone to dictate annotations to the system. In the prototype and testing system, the images used were aerial photographs of buildings, which have a somewhat regular shape and architecture, and . As the user points and speaks, an image processing algorithm attempts to determine the exact area of the image to be annotated, and the natural language processing engine attempts to format the user's dialogue, such as "This is Benedum Hall," into annotations for the system.

While this would be extremely efficient in theory, in testing the image processing algorithm was only able to correctly identify buildings 76.5 percent of the time. It also returned false positive buildings 2.9 percent of the time. Taking into consideration the lack of easily-identifiable demarcations in ophthalmic images to indicate appropriate annotation locations, at the current time at least, Show-and-Tell would be inappropriate for this application.

1.2.5 IBMAS

IBMAS, or Internet Based Medical Archive System, was also developed at the State University of New York, at Binghamton [8]. It is different from the majority of the other products and projects highlighted in this section in that the focus of the IBMAS project was to use a distributed database architecture (instead of file-based access either locally or through the Web) to enable users to share digital data in multiple modalities, such as text, images, CT scans, and speech recording, with other clinicians, regardless of physical locality. In IBMAS, users upload medical documents to a central database, perform annotation using speech or plain text, perform other data and image processing operations, and then select whether to have their document returned to them (in file form), or shared with the rest of the community (through database storage). This architecture is similar to the one used by Oxalis, in that a central database is used to store images to allow multiple remote concurrent accesses (see Chapter 2).

1.2.6 EyeScape Imaging Systems

The EyeScape Imaging Systems, manufactured by Synemed [9], represent an "end-to-end" solution for ophthalmic images. EyeScape systems are mounted directly to the clinician's slit lamp or non-mydriatic retinal camera, and are attached to a Windows-compatible personal computer. Once the image is taken, EyeScape stores the image as a file, and indexes it in a SQL-compliant relational database for faster searching. EyeScape is also capable of performing image annotation, although the exact capabilities in this field are not found in any material that has been made available to the public.

EyeScape therefore enables users to capture and annotate digital images, but does not provide any means other than email for users to share images or annotations. It is also unknown whether the annotation format will be made available to third-party developers, or if it strictly proprietary.

1.2.7 Software Development Kits

A number of companies have developed Software Development Kits (SDKs) for image display and annotation. A few examples are Snowbound Software's RasterNote SDK [10], AccuSoft Corporation's ImageGear [11], and Lead Technologies' LEADTOOLS Medical Imaging SDK [12]. However, all of the SDKs suffer from the same drawback: they are not useable products. In order for any of these libraries to be used by a clinician, the methods, controls, and display would first need to be implemented by a developer. Additionally, of the three mentioned SDKs, only LEADTOOLS offers a developer any method by which s/he could store the images and annotations to a database, as opposed to using file-based storage. A significant design and implementation effort would therefore be required to prevent a product designed using any of these SDKs from having the same inefficient copy-and-paste workflow as PAIS and I^2CNet.

2.0 SYSTEM OVERVIEW

In this chapter we present Oxalis from a user's perspective. We begin with a high-level architectural description of the system, and then proceed to describe the functionality available to a clinician. We provide a brief technical description of some of the key features, such as the expandability support, where it is appropriate to do so. For further technical details in the system's design and implementation, refer to Chapter 3.

2.1 High-Level Architecture

Oxalis consists of two main components: a database and client software. The two are connected either by being located on the same machine (the case for a single-user system) or over an intra- or intranet, as shown in Figure 1. The database is used as a repository for all data, including binary image data, for a group of users. The client software is a Java program, installed on the user's machine, which acts as the user's interface to the database. Using a Virtual Private Network (VPN) connection or dedicated dial-up, users in entirely different physical locations can share the same set of patient, image, and annotation data. This enables clinicians to have remote consultations with colleagues, regardless of their physical location.

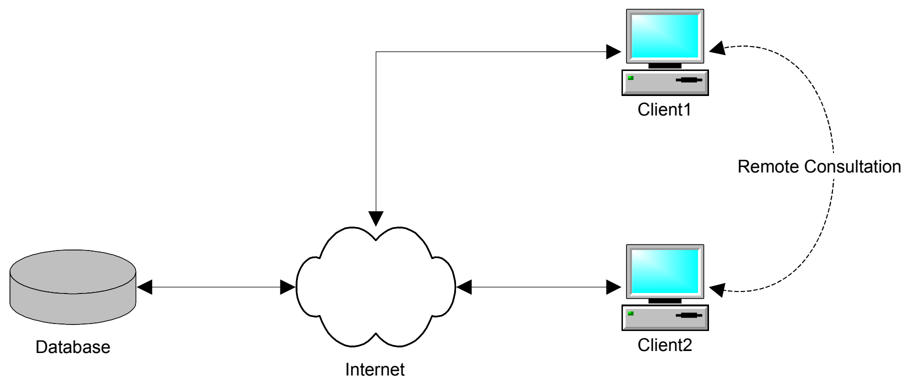


Figure 1. High-level overview of the Oxalis system.

2.2 Patient Records

The “base” record in Oxalis is a patient record. All image and annotation records are tied to a patient record. Therefore, in order to begin using the system to display and annotate images, the user must first either open a previous patients’ record, or create a new one. Currently, the system supports four fields: first name, last name, Social Security Number, and a generic status field. Figure 2 shows a user selecting a patient record. Using patient records as a starting point also helps the user find the right image quickly, as only images associated with the chosen patient record will be selectable.

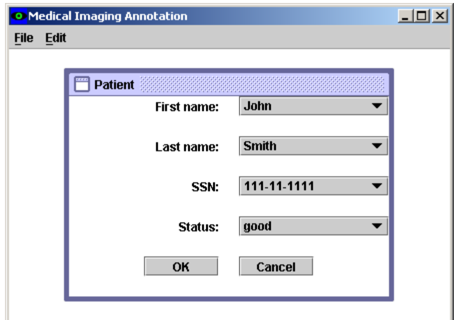


Figure 2. Open Patient Screen. The user is selecting to open John Smith's record.

In order to make the system as flexible and easily maintainable as possible, each record type (such as patient records) used by the system has a dedicated database wrapper class, which handles the vast majority of the queries pertaining to that record type. This makes it much easier to change the layout or fields of a database table, as the developer need only change the dedicated wrapper class (and any user interface components that directly display the table's fields). The only exception to this is when a foreign key field is affected by the change, in which case the table that is referencing the foreign key (and its associated wrapper) will also need to be changed.

2.3 Image Upload and Display

Once the user has selected or created a patient record, s/he can begin uploading images into the system. This must be done because of the "distributed" nature of Oxalis – if all images were stored on the user's local computers, it would be difficult (if not impossible) to effectively share patient and image information with fellow clinicians. Therefore, Oxalis stores all image data centrally, in a database, where it can be accessed by multiple users simultaneously with ease. This also helps system administrators perform backups of the image data, as they need only backup the main Oxalis computer's drive.

In order to upload an image to Oxalis, the user first selects to do so from Oxalis' menus, and then selects the image file from a standard "Open file" dialog box. See figure 3 (left) and Figure 3 (right), respectively. S/he can then add a text description of the image to the record. When the user clicks "Open", the image is uploaded to the database.

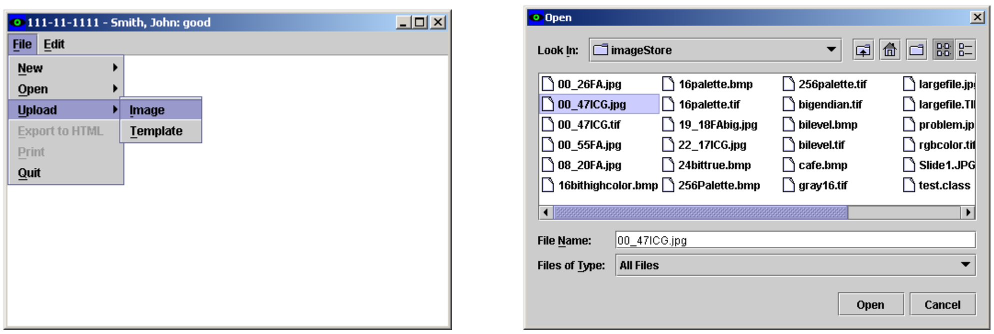


Figure 3. Image Upload. The user selects to upload an image file (left), and then chooses the file to upload (right).

Once the image has been uploaded, it is displayed by Oxalis. For future uses of the image, the user can select to open it from the main menu, and it will be "downloaded" to the user's software and opened. Figure 4 shows an Indocyanine Green (ICG) angiogram of a patient's retina, as displayed by Oxalis. Figure 5 shows a UML sequence diagram for the first three steps: logging in, creating a patient record, and uploading and displaying an image.

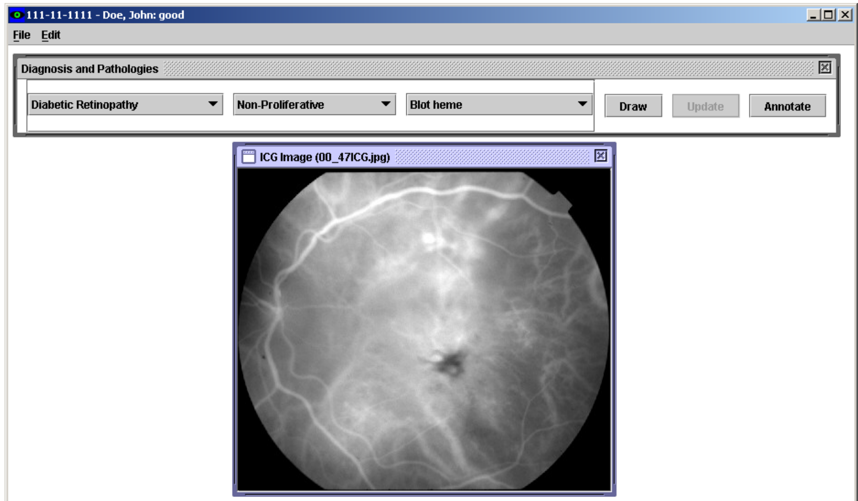


Figure 4. An Indocyanine Green image displayed by Oxalis.

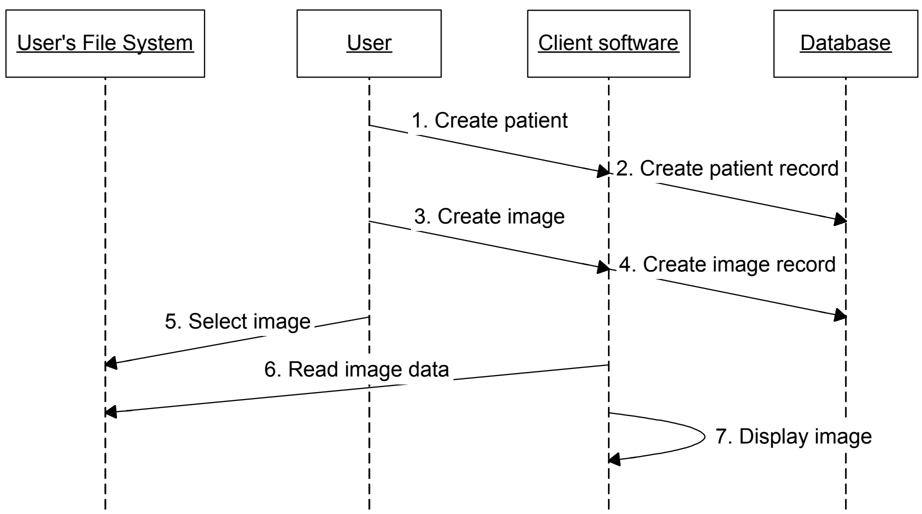


Figure 5. Sequence diagram for creating a patient record, uploading and displaying an image.

Image storage is accomplished using the binary large object (blob) datatype, which is found in most enterprise level database management systems. There are two primary reasons for this. First, putting the images inside the database provides an extra layer of security over the operating system, as an attacker must first gain control over the operating system and then either gain control over or decode the hashing and storage algorithms for the database. Second, storing the images directly on the server's file system would both needlessly increase the time to download an image (as it would require an extra connection to the server), and require administrators to maintain a separate set of login credentials (for the server's file system) for each user to determine whether or not they were permitted to upload images.

The classes that interpret image data have been designed to be easily interchangeable or expandable. This is accomplished using Java's reflective libraries, which allow an executing class to load other classes and libraries as needed at runtime. Currently, the system supports the Joint Photographic Experts Group (JPEG) [13], Tagged Image File Format (TIFF) [14], Graphics Interchange Format (GIF) [15], and Bitmap (BMP) [16] file formats, as these are the ones most commonly used in the digital devices used by ophthalmic photographers. However, due to the flexibility of the architecture, the Portable Network Graphics (PNG) [17], raw, or Digital Imaging and Communications in Medicine (DICOM) [18] file formats could be added to the list of displayable formats without changing or recompiling any of the core classes.

2.4 Diagnoses List

In order to annotate an image in Oxalis, the user must first select a diagnosis and pathology from the diagnoses list, visible at the top of Figure 4, and enlarged below as Figure 6. This leftmost dropdown box contains diagnoses, such as Diabetic Retinopathy, Age-related Macular Degeneration, etc. Making a selection from this box causes the next one to update: if the user selects "Diabetic Retinopathy" from the first box, the second one will contain "Proliferative" and "Non-Proliferative". Making a selection in the second box changes the third, and so on. The user can also select "Unknown", which will display a list of all available pathologies (for the case where the diagnosis is not known ahead of time). The use of the diagnoses list prevents users from accidentally corrupting patient records with typographical errors, and provides a common nomenclature for an entire installation.

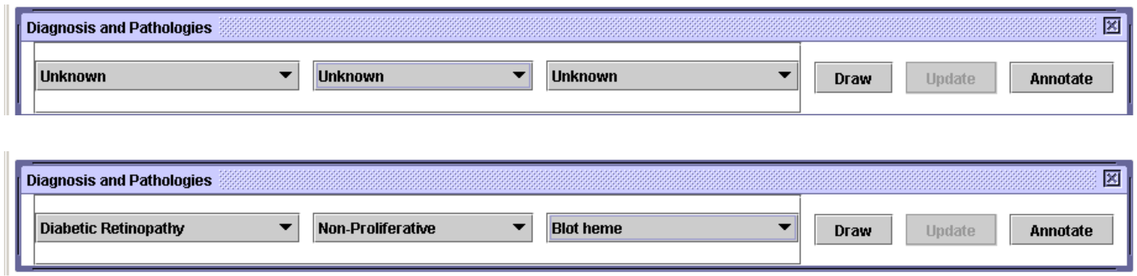


Figure 6. Diagnoses List. This figure shows the diagnoses list in its default configuration (top), and after the user has made a selection (bottom).

The diagnoses list is not "hard-coded" into the system. Instead, it is stored in the database, and can be changed or added to by any user. The list is presented to the user in "tree" form (like files in Windows Explorer) for editing, where "folders" contains all of the pathologies for the diagnosis. Users can copy, paste, remove, or add to the list, as well as editing individual entries. In order to ensure the integrity of an image review, if a user changes a list item (for spelling, to change from an acronym to the full name, etc.) that has been used on an image, the annotation on the image will remain as originally specified. However, the changed list item will no longer be available for selection for future uses. Changes to the tree by a user are reflected immediately in the list for all users. See Figure 7 for an example of editing a diagnoses list. For these examples, we have used a set of common, informal ophthalmic diagnoses and pathologies; however, the flexibility of the lists allows for a much more formal and specific classification to be accomplished. One such possibility is using the International Classification of Disease (ICD) [19] codes.

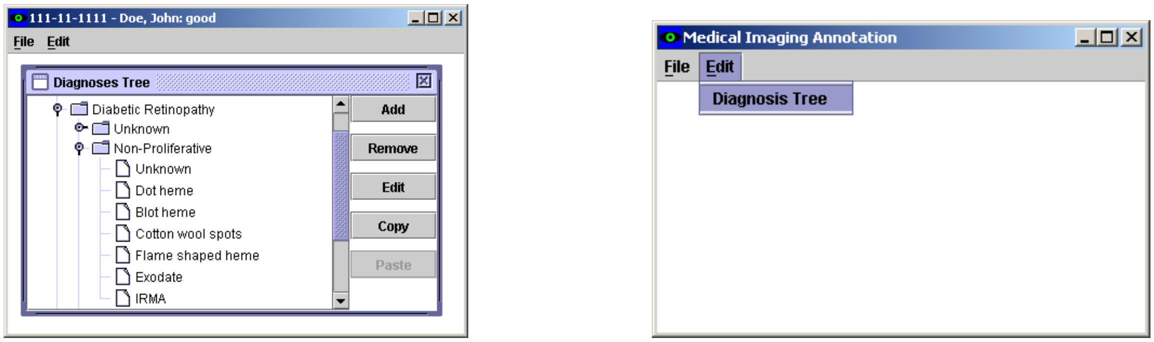


Figure 7. Diagnoses Tree. A user elects to edit the diagnoses list (left) and is presented with the list in tree form (right).

The table structure for the diagnoses list/tree is shown in Figure 8. Of special interest is the “parentnum” field, which recursively references the “identifier” field. This sets up the parent-child relationship in the list, and enables the hierarchy of the data to be only limited by the length of the “identifier” and “parentnum” fields. Currently, the fields are each specified as ten numeric digits long, for a total of ten billion entries.

The transformation has been optimized to only retrieve the list from the database when the system initializes or a change is made to the list on a different computer. On all other occasions, the “tree view” is directly transformed (by “walking the tree” in bottom-up order) into the list in memory. For large lists/trees and slow network links, this optimization results in a phenomenal improvement in performance. However, even over a 100 Megabit per second link, the time to rebuild and display a forty-item list in memory was measured to be roughly half of the time to requery the database (four seconds versus 8.5 seconds).

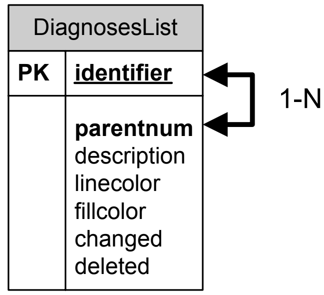


Figure 8. Entity-Relationship model of the diagnoses list.

2.5 Annotations

Once the user has selected the appropriate annotation from the list, s/he clicks the “Draw” button. The user then presses her primary mouse button over the image, and “drags” to create a freeform polygon. See Figure 9 (top left). When the user releases the mouse button, the annotation is automatically sent to Oxalis’ database for storage.

Once an annotation has been created, the user can click on it to select it (if it isn’t already selected) and move it around the image (if necessary). The user can also select to hide an individual annotation or all annotations on an image temporarily, and later restore them to view. Additionally, the user can resize or reshape an annotation by selecting one of the “clip points” (black rectangles over the vertices of the polygon) and “dragging” it. As the speed of the drag increases, clip points neighboring the dragged point move with it (to a lesser extend), in order to save time when making major corrections to a region. Finally, the user can elect to “delete” an annotation. In order to preserve the integrity of diagnostic records, “deleted” annotations are never permanently removed from the database, rather, they are marked as “undisplayable” and, as such, will not be downloaded or displayed for a user unless he or she specifically select to view deleted annotations. See Figure 9. Figure 10 shows a sequence diagram for creating the diagnoses list, selecting a pathology, and annotating an image.

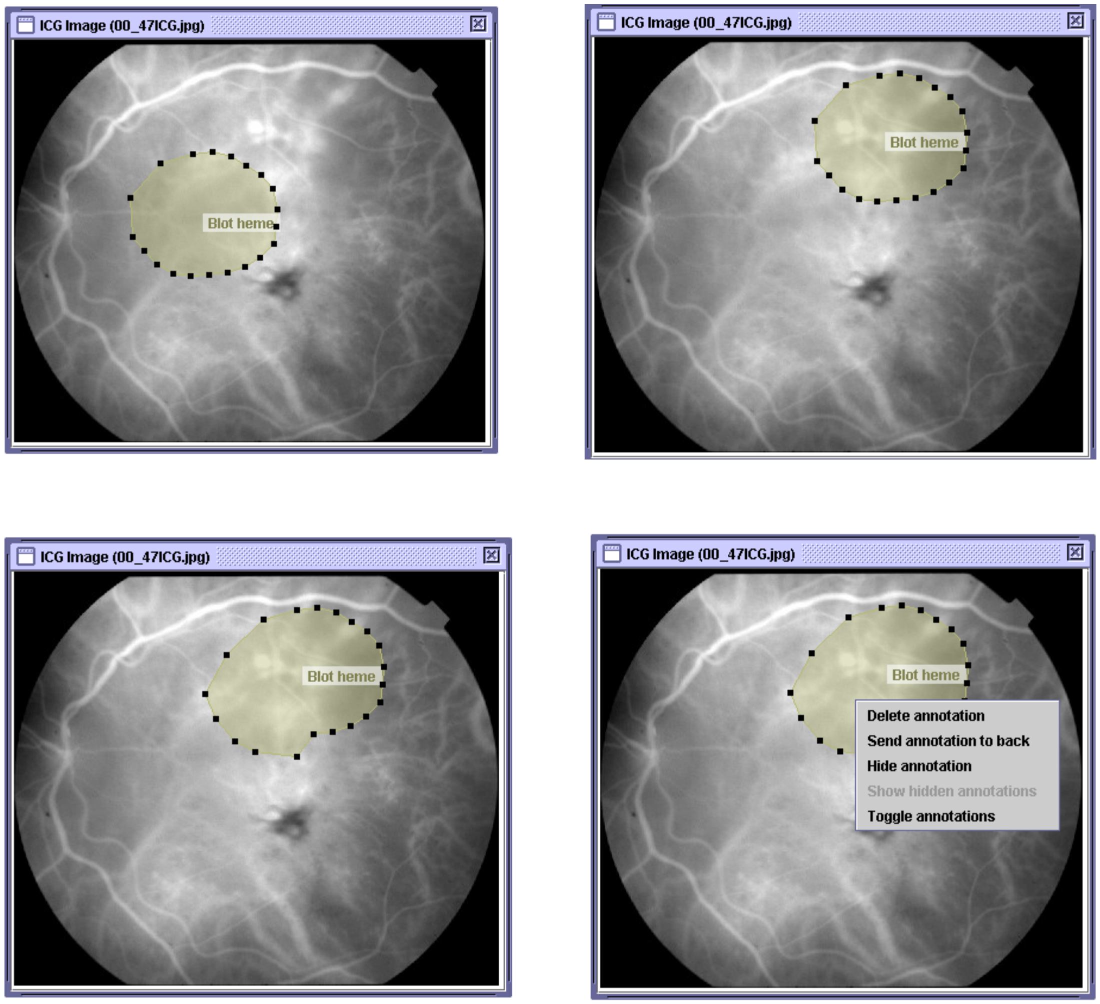


Figure 9. Image Annotation. The user has created an annotation on the image (top left). Note that the annotation color is semi-transparent. Colors are based on the selection in the diagnoses list. The user then moves the annotation into position on the image (top right). Next, the user reshapes the annotation slightly to refine the annotated region (bottom left). Finally, the user activates a context-sensitive menu for the annotation (bottom right).

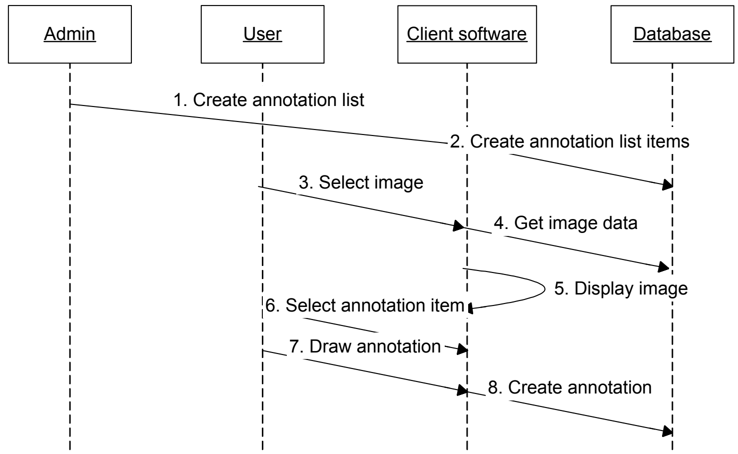


Figure 10. Sequence diagram for creating an annotation.

Annotations are drawn as Java Polygon objects, with a semi-transparent fill Color selected. To allow for annotations to be easily tracked for updates, each is given its own (fully transparent) container, which are stacked in a z-aligned array the same size as the image. The container for an annotation is responsible for handling all mouse and keyboard events pertaining to it, and reporting to the database wrapper and the other members of the array.

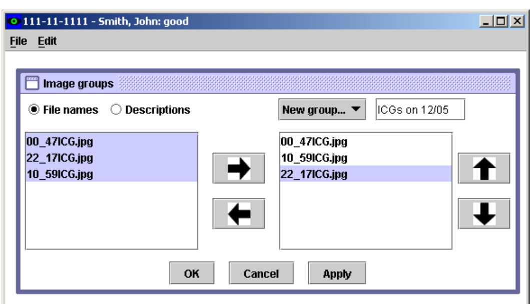
The rate at which vertices are added to an annotation's Polygon during creation is controlled by the distance the mouse has moved. This field is maintained with a user's profile in the database, and can be changed by the user at any time.

All of the data operations for annotation creation and update are performed when the user releases his/her mouse button following a change. This provides a balance between the desires to have the data immediately available for other users, and not to perform an unnecessary number of updates (especially true for slow network links).

2.6 Image Groups

Generally, Florescein and Indocyanine Green angiography is not accomplished with a single image. Instead, multiple images are taken at a fixed time interval as the dye takes effect. To best display these images, Oxalis enables the user to create an image group, or sequence of images, which can be displayed as one entity and "scrolled" through by the user.

In order to create an image group, all of the images in the group must first be uploaded to the database. The user then selects the images in the image group creation screen, and "sends" them to the group by clicking the right arrow icon. The user can then change the order of the images within the group by clicking the up/down arrow icons, and remove an image from the group by clicking the left arrow icon. Finally, the user can assign the group a name, and click "OK" to create the group. See Figure 11.



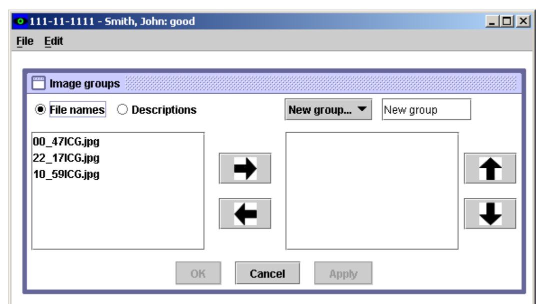


Figure 11. The user has selected to create a group (left). The user then selects and orders the images, and gives the group a name (right).

Once the user has created the group, it is automatically displayed by Oxalis. See Figure 12. When the user clicks the scrollbar at the bottom of the image, Oxalis advances or rewinds the "frame" of the sequence, displaying images in the order specified during group creation. This enabled clinicians to clearly and easily see the changes as the dye takes effect. Any annotation performed on an image within a group will always be displayed either with the group or when the image is opened individually. Additionally, any annotations already present on a grouped image will be displayed in the group. Figure 13 shows a sequence diagram for creating an image group.

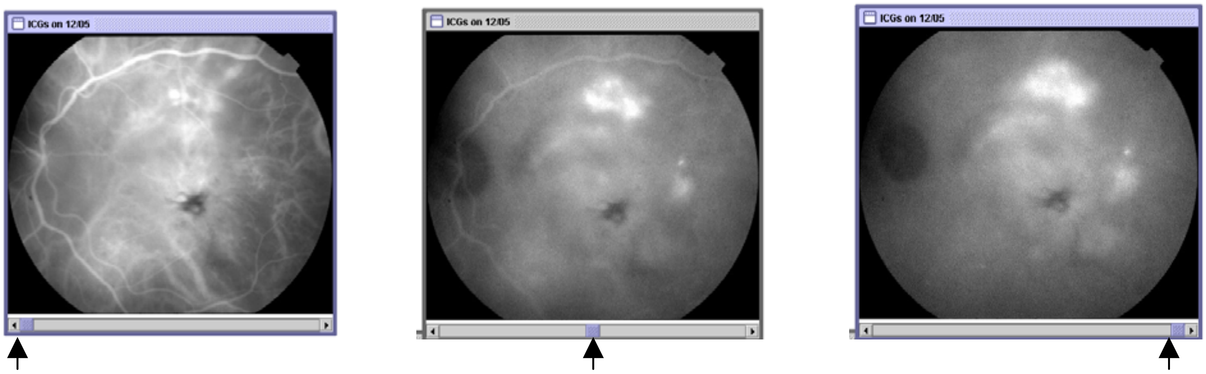


Figure 12. Three images within an image group. Note the position of the scrollbar, indicated by arrows. This group was created as an example, and may or may not represent three images from the same patient.

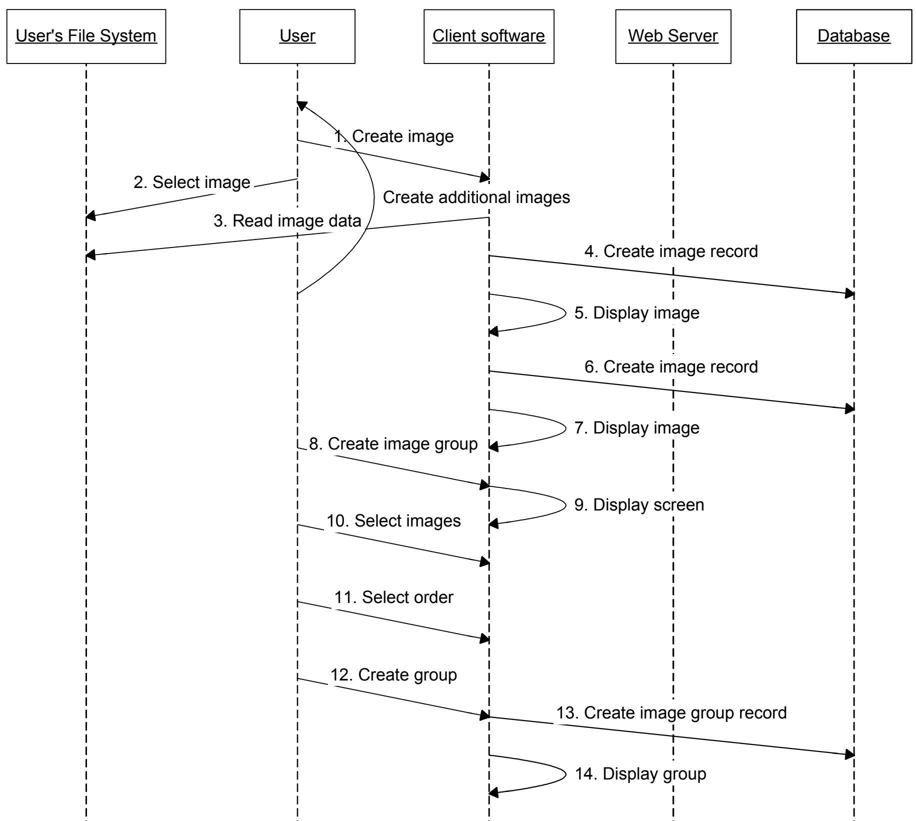


Figure 13. Sequence diagram for creating an image group.

2.7 Templates

There are situations in ophthalmic photography where it may be unclear which section of the eye was being studied for a given photograph. In these cases, it would be much more clear if the photographs could be "hyperlinked" to a schematic or line drawing of either the retina or the entire eye.

Oxalis enables the user to do this using "templates", or pre-uploaded schematics. These images are stored and displayed exactly as any other (so a template could be a photograph instead of a drawing), but, instead of being annotated with pathologies and diagnoses, are annotated with hyperlinks to images or image groups. Figure 14 shows a template image of the retina.

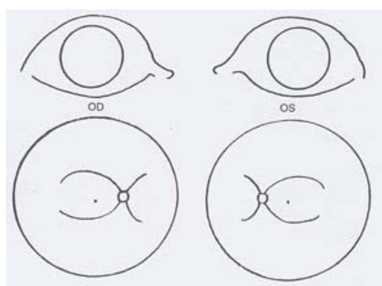


Figure 14. A fundus (retina) template image. The upper images depict the retina in relation to the eye. The lower images detail the retina itself.

In order to distinguish between hyperlinks and regular annotations (which cannot be created on a template), hyperlinks are drawn as rectangles instead of freehand polygons. The position where the user initially presses the mouse button becomes one corner of the rectangle, and the other three vertices "drag" with the user's mouse movement. Once the user releases the mouse, a dialog is presenting, asking the user to assign an image to this hyperlink. If the user does so, a thumbnail of the image is displayed in the fields to the right or left of the template image. Clicking on the thumbnail, or double-clicking on the rectangle on the template image, will cause the system to open the linked image. Figure 15 shows a completed template image. Figure 16 shows the sequence diagram for creating and annotating a template.

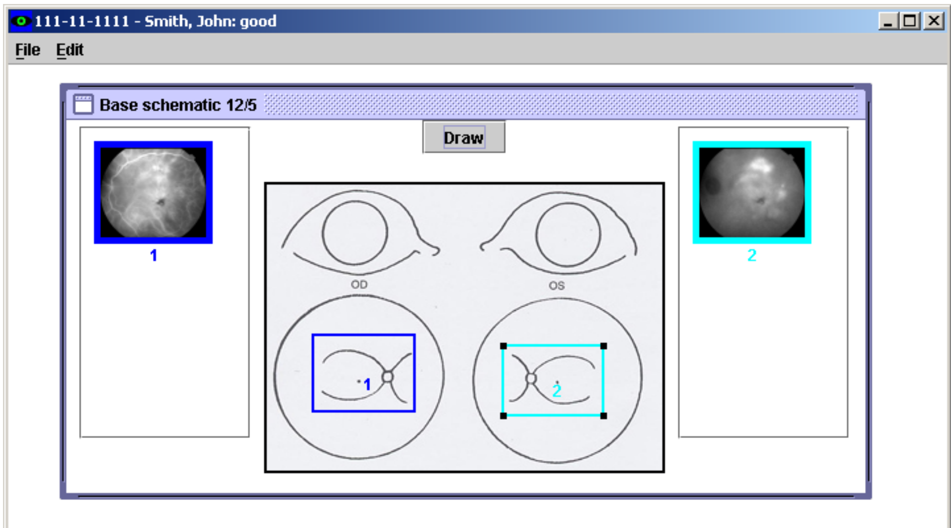


Figure 15. Completed template image.

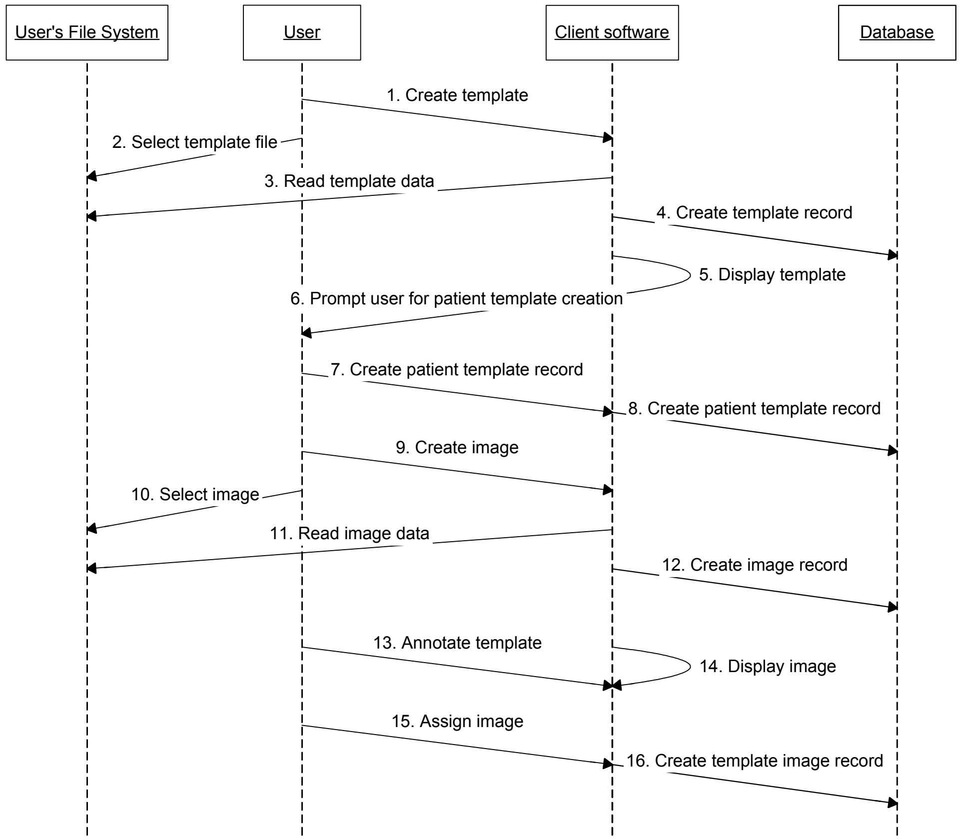


Figure 16. Sequence diagram for creating a template image.

Both the image group and template functions use the predefined image display architecture to display their images. They are extensions to the architecture, and required very minimal changes to the other classes to implement. Due to the fact that an Oracle database is used as the primary development environment for the project, and that Oracle is not in compliance with the JDBC driver for binary large objects, changes to the primary database wrapper were required to implement the storage and retrieval of template images, but otherwise the addition of these features consisted of the addition of a few new tables to the database, a small amount of new code to handle the features themselves, and a number of calls to other portions of the architecture to perform the actual “work” of the features.

3.0 TECHNICAL DETAILS OF ANNOTATION

In order to enable users to efficiently display, annotate and share images, a number of different features needed to be designed and implemented. First, an initialization system needed to be designed. The main requirements for this system were that it allow users to easily change their "home" database, and enhance, update and control the image display capabilities of Oxalis.

Second, the system needed a way for components to be notified of the creation or modification of data records. The most important data records for the system the ones concerning patients, images, and annotations. Many system components need to be notified whenever a change occurs in any of these, a many-to-many relationship. It was therefore imperative for the notification method to be efficient, both in implementation and in execution.

Third, the image data interpretation and display panels needed to be designed to enable developers to efficiently modify or implement new image formats and specifications. Image file formats are constantly being developed and modified, and it is important for the system to be able to keep abreast of these changes. If a new format could not be added to the system in a well-defined manner, it would greatly reduce the useable life cycle of Oxalis.

Fourth, annotation panels, which perform the drawing and display operations for annotations, needed to be designed perform as quickly and effectively as possible. This included designing an efficient annotation painting algorithm, so that the system would not be excessively burdened redrawing annotations as the user performed a manipulation. It also required that a balance be achieved between the user's desire to have data available immediately, and the desire to perform as few updates to the database as possible, so as not to waste processor time and network bandwidth on unnecessary updates.

Fifth, it was decided that the standard approach taken by many of the currently available systems, of allowing the user to enter plain text for annotations, was inefficient for users, who have to enter similar information each time, and for database storage, as the same description must be archived repeatedly. As a solution to this problem, the concept of a selectable list of available annotations was developed. In order to complete the design of this component, it was necessary to provide users with a graphical editing tool for the selectable list.

Finally, in order to allow annotated images to be as portable as possible, it was necessary to provide users with a method to export their images and annotations from Oxalis to a commonly available file format. The formats decided on for this were JPEG images, and HTML/JavaScript files, which enables images annotated in Oxalis to be publishable to the World Wide Web. Additionally, in order to allow developers to extend the capabilities of Oxalis, it was necessary to provide a central data aggregation component, which is guaranteed to contain the most current data being used by the system. During design, these two goals were tied together, with the data manager being designed first, and the component that performs the export to HTML serving as an example of how a component can interact with the data manager.

Each of these components will now be described in detail.

3.1 Initialization

One of the goals in the design of Oxalis was to make it a distributed system, giving users the ability to easily share information regardless of physical locality. To accomplish this, we use a database to store all file, image, and annotation data centrally. However, in certain situations, it is necessary for a user to connect to more than one Oxalis database. One such situation would be a remote consultation, when a clinician from a different hospital or health system would be called on to diagnose a patient. In this case, it would be much more efficient for the patient's data to be entered in the database closest to him/her, as opposed to the one nearest the consulting clinician. However, it would be both inefficient and burdensome for a user to have to edit and recompile Java source code in order to switch databases.

A related design goal was to have the image interpretation performed by Oxalis be easily configurable by the user without having to edit and recompile the source code. Image formats and specifications are constantly being updated, and new formats are continuously being developed. The past seven years have seen the advent of PNG (1995), several updates to the Digital Imaging and Communications in Medicine (DICOM) standard (2003), and the advent of JPEG2000 (2000), among other changes. In order for Oxalis to change with image specifications, there must be a method for a single developer or group of developers to implement the changes to the image processors, and then deliver these changes to users. Most importantly, it must be relatively simple for a user to add, change, or update an image interpreter on his or her own Oxalis installation.

In order to solve both of these problems, Oxalis uses an initialization file. This file contains all of the information needed to connect to a local or remote database, as well as all of the information necessary to install and initialize the image processors used by Oxalis. An eXtensible Markup Language (XML) file is used for initialization because it can be specified and checked using a Data Type Declaration (DTD) [20] to prevent typographical errors from halting initialization, and parsed using the Java API for XML Processing (JAXP) [21]. A sample XML initialization file for Oxalis is shown in Figure 17. The rest of this document describes the elements of this file in detail, and describe the steps necessary to either change the user's database, or install or remove an image processor.

```xml
<?xml version="1.0" encoding="ISO-8859-1"?>
<!DOCTYPE root-element SYSTEM "OxalisINI.dtd">
<Oxalis>
	<database>
		<driverClass>database.MySQLImagingDatabase</driverClass>
		<host>localhost</host>
		<db>someDB</db>
		<username>sample-user</username>
		<password>sample-pass</password>
	</database>
	<imageInterpreters>
		<class>imagedisplay.JPGGIFImageDisplayPanel</class>
		<class>imagedisplay.TIFImageDisplayPanel</class>
		<class>imagedisplay.BMPImageDisplayPanel</class>
	</imageInterpreters>
	<userPrefs>
		<listLength>50</listLength>
		<pointSpacing>15</pointSpacing>
	</userPrefs>
</Oxalis>
```

Figure 17. Sample XML initialization file for Oxalis.

The first two lines of the file contain the XML version and encoding scheme, and the metadata used by JAXP to validate and parse the file. After this comes “<Oxalis>”, the root element for this file. All of the initialization parameters are child elements of Oxalis, as required by the XML specification.

The first child element specifies the source database. It contains all of the information Oxalis will use to initialize, connect to, and interact with the database. The first subelement in this group is the database “driverClass,” which is the fully qualified name of a Java class that implements the database.ImagingDatabase interface. The remaining parameters are the host (Domain Name System [DNS] name or Internet Protocol [IP] address), database identifier (as required by the Database Management System), username, and password. These four parameters will be passed as Strings to the driver during construction. Actual initialization of the database driver is accomplished reflectively using Java’s Constructor class [22].

The next child of Oxalis is the “imageInterpreters” element. This element contains all of the subclasses of imageDisplay.ImageDisplayPanel that will be initialized reflectively (using Class.forName) for use in interpreting and displaying images. This example file initializes a panel to handle JPEG, GIF, TIFF, and BMP images. Once these panels are initialized, they will be registered with the ImageDisplayFactory, and called on to process image data and display images as needed.

The final element is titled “userPrefs”, and contains preferences for individual users. The two child elements included in this sample file set the number of items displayed in the diagnoses list before scrolling to fifty, and the number of pixels in between point locations in an annotation to fifteen.

Using the XML initialization file, it is a relatively simple process for a user to switch between several imaging databases in different locations. Instead of altering the location in code and recompiling, all that needs to be done is to change the children of the “database” element. As the initialization filename is specified at runtime, if a user needs to frequently switch between databases, s/he can create multiple instances of the initialization file, and specify the correct one for each application.

It is also much easier to add or disable an image interpreter than fully editing and recompiling the source code. In order to add one, a developer must first subclass imageDisplay.ImageDisplayPanel. S/he then compiles the class, and distributes it. Users can then add the class to their Java ARchive (JAR) file, and add the class’ name as a child of their imageInterpreter element by editing the XML file. Disabling an image interpreter consists entirely of removing its child element from the imageIterpreters node in the XML initialization file.

3.2 Event Model

Oxalis enables the user to have multiple images, image groups, and image templates open at any given time, and each of these images can have multiple annotations. However, there are many system components that must be notified whenever any of the images or annotation records change, or when new records are created. One possible solution to this would be to have each component that can change or create a data record directly call a method on each component that must be notified of these changes. However, the implementation of this solution would be inefficient, as each new system component that requires notification would need to have its methods added. Both the component performing the modification or creation and the new component would then need to be rebuilt.

Instead of a strictly hard-coded approach, Oxalis uses a series of *data events* and *data event handlers* to pass information and notifications around the system. Data events are events that are fired whenever the user creates, modifies, or removes a data record. Data event handlers are system components that are capable of receiving and processing data events. An example of a data event is when a user deletes an image, the corresponding handler for this event could provide a confirmation window and/or place a copy of the image in a "recycle bin".

The three main record types which require this event model to be in place are 1) patient records, which contain all of a patient's data as well as serving as the parent data for the other records; 2) image records, which contain the image's description, file name, and binary raster data; and 3) annotations, which contain the series of points outlining the shape, as well as the text and color of the annotation.

The realization of this design in Oxalis uses an event model similar to the one used by the standard Java Abstract Windowing Toolkit (AWT). Components that wish to be notified of a data event implement a “listener” (handler) interface for that event. Components that will dispatch notifications of these events have an “addListener” method, which adds a handler to the list of components that will be notified when the event is triggered. An example from the AWT would be a component that wishes to be notified when a button is pressed. The component, the handler in this example, implements the ActionListener interface, and its single method, actionPerformed. The button, the firing component in this example, has an addActionListener method, which adds the component to the list that will be notified when the button is pressed.

In Oxalis, the three main events are succinctly named PatientEvent, ImageEvent, and ShapeEvent, respectively, and the handlers for each of the events are named PatientListener, ImageListener, and ShapeListener. System components that generate these events have an “addListener” method which allows a handler to be added to the list that will be notified when the even is thrown. Each of these events, together with their trigger conditions, data, and requirements to be notified of them, will now be described in detail.

A PatientEvent is fired whenever a patient’s record is opened, closed, deleted, modified, or created. These events are fired by the NewPatientPanel and the OpenPatientPanel, and are dispatched to any object that has implemented the PatientListener interface and registered with the panels through the addPatientListener method. The addPatientListener method is static in each class, allowing an object that wishes to receive patient events to register to do so regardless of the order objects are initialized, and without having either of the panels passed via the constructor or by searching the ClassRegistry. A large number of objects in the default Oxalis distribution register to receive PatientEvents, as all images (and image lists) are tied to patient records.

An ImageEvent is the image counterpart to the PatientEvent. They are fired by the ImageOpenPanel and ImageUploadPanel, and dispatched to all objects that have implemented the ImageListener interface and registered to receive events via the addImageListener method. Like their counterpart patient panels, these methods have also been declared static to allow for the easiest access by other objects. Currently, the ImageListener interface is used mainly by the main Oxalis object (to display images once they have been created or opened) and the DataManager interface (to maintain a reference to the currently-opened image for export and other purposes).

ShapeEvents are a slightly different type of event. They are fired by individual PolygonPanels (for images) and RectanglePanels (for templates) when the user begins or finishes drawing a new annotation, or modifies, selects, deselects, or double-clicks on an old annotation. In order to receive these events, an object must first implement the ShapeListener method, and second register with the appropriate BasePanel that contains the annotation panel firing the event. As there can be multiple BasePanels in existence at a given time, and not all objects wish to receive all shape events, it was not possible to declare the addShapeListener method static. However, for objects that do wish to receive all ShapeEvents from the system, the BasePanelFactory and TemplateDisplayFactory contain static versions of these methods which will cause the object to be registered with every BasePanel or TemplateBasePanel that is created.

Each of the three events contains three methods in addition to the constructor: getSource, which returns the component panel that originated the event; getData, which returns an event-specific record that pertains to the event (e.g. an ImageRecord for an ImageEvent) and getType, which returns an integer code identifying the type of event. These codes can be matched with statically declared variables in each event to provide further information to objects receiving the event.

In addition to the benefits from enabling system components to be efficiently notified when data records are created or modified, the event model also enhances the extensibility of the system. A developer designing a component that needs to be notified of changes to patient, image, or annotation records can implement the appropriate listener methods, and add his or her component to the list that will be notified when the even occurs. This enables developers to receive and handle the data event without first needing to edit the core component responsible for generating the event. A future direction for the event model would be to design an intermediary component which performs all registration of both handlers and event generators. This component would index the methods required for handler implementation reflectively at run-time, and map capable handlers to the appropriate event generators. This would provide a central point for both handlers and generators, without needing any knowledge of the component generating or the components receiving the event. It would also enable developers to extend the event model itself by registering a generator for a new event type.

3.3 Image Panels

As previous stated, one of the design goals for the Oxalis system was to allow developers to quickly extend or modify the image handling capabilities of the system, and to allow users to easily control the image handlers that are installed. The creation of the XML initialization file offers a solution to the second half of this problem, but does very little to alleviate the first part. In order for developers to be able to quickly design and implement a processor for a new or updated image specification, it was necessary to design Oxalis such that a clear and wellstructured specification for how the system chooses an image reader and displays an image could be given to developers.

The specification for an image interpretation and display component in Oxalis uses an abstract parent base class called ImageDisplayPanel. Any panel that wishes to display images for Oxalis must subclass this panel. In return, developers can be guaranteed that only the methods present in ImageDisplayPanel will be called by Oxalis, and can be made aware of exactly what the system expects when each of these methods is invoked. The three methods present and declared abstract in ImageDisplayPanel are getDisplayableTypes, setImageRecord, and getImage. Each of these methods will now be described in detail, followed by an example sequence of the system loading an image handler and displaying an image.

The first ImageDisplayPanel method, getDisplayableTypes, returns an array of type String. Each element of this array is expected to be a file extension (such as JPG, GIF, or TIF) that this ImageDisplayPanel wishes to provide display capabilities for. If two panels register to handle the same type of image, the one which is processed last during initialization will be the one that is used.

The second ImageDisplayPanel method, setImageRecord, sets the panel's sets the panel's image data for display. Once this method has been invoked, the panel should immediately process the image data and display the image. It should also set the preferred size, minimum size, and maximum size to be the size of the image, so that layout managers will be able to correctly lay out the component. When this method returns, the ImageDisplayPanel is expected to be fully rendered (or pre-rendered) and ready for display.

The final ImageDisplayPanel method, getImage, returns the image this panel is displaying. This can then be processed directly by export or rendering methods more advanced than simply displaying the image.

Once a new ImageDisplayPanel has been created and compiled, only two steps need to be accomplished by a user or administrator for it to be installed. First, the class file must be copied into the user's Java ARchive (JAR) file with the other components of the system. Second, an entry needs to be added to the user's XML initialization file under the imageInterpreters element, which gives the fully qualified class name of the ImageDisplayPanel.

As shown in Figure 18, the main Oxalis object does not directly instantiate ImageDisplayPanels through a call to their contructor. Rather, it delegates this responsibility to the ImageDisplayFactory object. This object is responsible for indexing the displayable types of each of the ImageDisplayPanels, selecting the correct type of ImageDisplayPanel when Oxalis requests that an image be displayed, instantiating the panel, and causing the panel to render the image. The ImageDisplayFactory then returns the panel to Oxalis, ready to be displayed.

During initialization, each entry in the imageInterpreters section will be parsed by the system, and the Class object for each will be passed to the registerImageDisplayPanelType method of the ImageDisplayFactory. There, it will be checked to ensure that it is a subclass of ImageDisplayPanel. If it is, it will be asked for the file types it wishes to display (via the getDisplayableTypes method), and added to the ImageDisplayFactory's cache of displayable panels.

When the user opens an image, Oxalis calls the ImageDisplayFactory's createImageDisplayPanel method, which searches the cache for the appropriate panel, invokes the panel's setImageRecord method, and returns the panel to Oxalis for display.

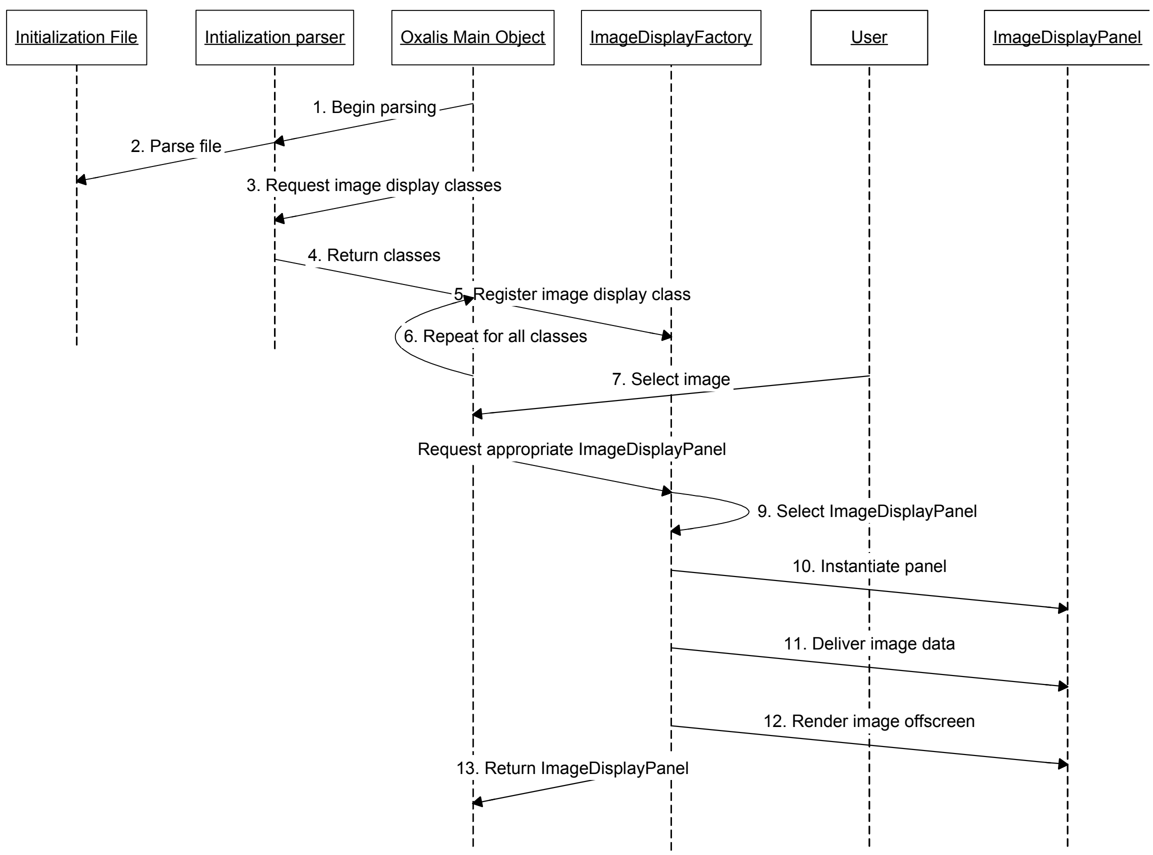


Figure 18. Sequence diagram for initializing, selecting, and displaying images.

This system, involving reflective loading, caching, and implementation of an abstract class, allows users and developers to easily extend the image display capabilities of Oxalis. For the sake of comparison, the steps necessary for a strictly hard-coded implementation of image display capabilities would require a developer to create and compile the image display class, and then either obtain and compile the user's current installation classes or give the user precise instructions in the changes needing to be made to the registering classes. The user would then need to make these changes, and rebuild the entire source code.

3.4 Annotation Panels

In order to make the process of annotating an image as easy and efficient as possible for the user, three main issues needed to be resolved. First, due to the large number of shapes that would likely be present, and the semi-transparent nature of the shapes, a highly efficient algorithm for drawing and coloring (painting) the annotations needs to be developed. An inefficient painting algorithm would result in several problems, such as a noticeable time in between the background being painted and a shape being painted (flicker), a shape not painting synchronously to the user's mouse movements (lag), and increased processor and memory utilization. Second, the user should have maximum freedom in deciding how their shapes are drawn. This includes configuring the number of points per circumference, the total number of points and the rate at which points are placed on a polygon. Third, a balance needs to be achieved between user's desire to have the annotation information instantly available in the database (so that it can be accessed by other clinicians) and the user's desire to not have to wait for a database update to occur every time s/he moved the mouse during an annotation.

To maximize the efficiency of the painting algorithm, Oxalis places the annotations into a "stack" of panels using Java's JLayeredPane object. Each panel in the stack contains one annotation, and performs all of the painting and movement for only that annotation. As the background of each of the panels is transparent, only annotation shape needs to be repainted, and the painting process can be "clipped" (narrowed in scope) as a result. Therefore, instead of repainting the entire panel, only the bounding box around the shape is painted.

The user's mouse events (such as clicking, movement, and drag) are intercepted by the highest annotation panel in the stack. If a panel determines that the event does not apply to its annotation, because the user has clicked outside the shape or the shape is unselected, for example, the mouse event is forwarded to other annotation panels for processing.

For the sake of comparison, assume all of the shapes had been placed in the same panel. Because shapes can overlap and intersect each other, it would be necessary to either repaint the entire panel every time the user manipulated a shape, or calculate the area in which the user's current shape intersected other shapes and add that area to the section to be repainted. Either of these methods would require a much larger amount of processing and/or painting time than the method presented above. It would also be necessary to implement an algorithm to control the "z-order", the height of each shape relative to the user's eye (which controls how shapes overlap each other). Furthermore, it would be necessary for the containing panel to perform a search through all of the shapes to determine which one to apply a mouse event to.

To solve the problem of enabling users to configure the rate at which points are placed, and regulate the number of points placed per annotation, the first item that was required was an algorithm for deciding exactly how and when to place points on an annotation. The standard Java Runtime Environment (JRE) fires mouse events (most notably movement or drag events for this application) on a fixed time interval, regardless of the speed with which the user moves the mouse. This means that a slow steady mouse drag fires more mouse events than a quick one. This has a decided impact on the algorithm chosen, as an algorithm that relied on the number of mouse events that had occurred would multiply this effect, resulting in far fewer than the desired number of points being created if the user moved the mouse hurriedly. Therefore, the point placement algorithm used by Oxalis is based on the distance in between the location of the current mouse event and the last point added to the annotation shape. This is still subject to the JRE's policy of firing mouse events, but is guaranteed to place a point at the location of the first mouse event beyond the desired distance. Finally, the distance field is added to the initialization file under the "userPrefs" element, as this is more efficient for users than editing and recompiling source code.

The third problem, balancing the number of database updates with the desire for immediate information availability, concerns both network bandwidth utilization and user efficiency. There are two extreme cases. In the first case, the database is updated every time the user performs an operation, from moving an annotation one position to beginning to draw a new annotation. This results in both high network utilization, as an extreme number of database updates would congest the route between the user's computer and the database, and poor performance, as the user's machine must wait for each update to occur. In the second extreme case, the database is only updated when the user logs off or closes the image. This results in bandwidth utilization that is low on average, but contains sharp peaks whenever the user performs one of the update operations. It also results in poor performance for other users, as they must wait for the image to be closed on the user's system before updates will be reflected on their systems. To balance between these two extremes, Oxalis performs a database update on an individual annotation when the user *releases* the mouse button after s/he has performed an update to an annotation. This results in an average, but relatively constant network utilization, as updates are only processed once per change (the user first presses the mouse on the annotation, then drags it to perform an update, then releases it). It also results in better performance for both the current user and other users, as the updating user only needs to wait for one database update to be performed per change, and other users only need to wait for the updating user to release the mouse button in order to obtain the most current data.

The achievement of these three objectives allows Oxalis to function in a efficient and professional manner. This, in turn, enables users to efficiently annotate images, and have access to annotation information provided by others, which is the over-arching goal of the Oxalis project.

3.5 Diagnoses List and Diagnoses Tree

As previously noted, the vast majority of currently available image annotation systems use plain text, entered by the user, to annotate the image. However, using this method could result in uncertainty of diagnosis, caused by either a typographical error or a difference in notation (such as one clinician using an acronym to describe a pathology while another does not). It is also inefficient, as diagnoses and pathologies must be typed by clinicians each time, and stored as a unique string in the database. While an "intelligent agent" or natural language processing system, such as Aria [23], the Remembrance Agent [24] or the Papillon representation system [25], which fill in the remainder of a word or phrase once a user has typed an identifiable portion of it, could assist users in making annotation more efficient, the redundant occurrence of text descriptions in the database would still exist, as would the possibility of uncertainty in diagnosis.

As an alternative to plain text annotation, Oxalis users select from a pre-defined set of lists of annotations, and then draw the selected annotation on the image, instead of entering text-based descriptions. This is similar to the "concept-based approach" described by Gertz et al. [26] See Figure 19 for an example list of possible annotations. This method eliminates the uncertainty of text-based annotations, as all users in a particular institution or clinical setting are forced to use the same notation. It also eliminates the redundancy of information in the database, as the description of the annotation is only stored with the list itself.

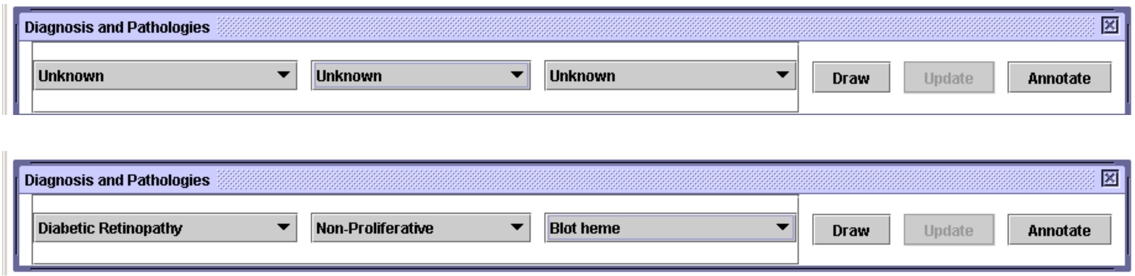


Figure 19. Annotation list. In the top figure, the list is shown in its default configuration. In the bottom figure, the user has selected "Diabetic Retinopathy", "Non-proliferative", and "Blot heme."

In order to maximize user efficiency and enable users to develop their own format and nomenclature (or implement a known standard such as the International Classification of Disease codes), it is necessary to provide a graphical method for users to edit the contents of the list within the Oxalis system (as opposed to editing the database directly) and allow the sequence of be as long as the user desired. This posed several problems. First, a table structure needed to be developed that could accommodate the diagnoses list. Second, methods needed to be developed to allow the user to efficiently edit the contents of the table, and transform the table to the sequence of lists used for annotation.

The Entity Relationship Diagram (ERD) of the database table for the diagnoses list is shown in Figure 20. Each item in the diagnoses list has a unique integer primary key stored in the field "identifier." Additionally, each list record must contain an integer in the "parentnum" field, which is tied by a foreign key constraint to the "identifier" field. The integer found in the "parentnum" field uniquely identifies the record which will serve as the parent of this record in the list and tree. This system enables the list or tree to be efficiently stored and practically unlimited (currently 10^{10}) in length or width. The next four elements, “description”, “linecolor”, “fillcolor”, and “altText”, control the appearance and text of the diagnoses list item, indicating (respectively) the full description, the color the outline of the shape will be rendered in, the color the shape will be filled with, and the text that will be displayed with the annotation.

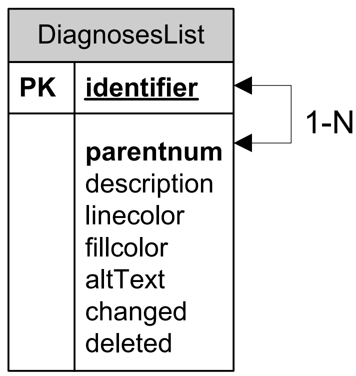


Figure 20. ERD for the diagnoses list table.

Three example records for the table are shown in Table 1. Note that the “ParentNum” of the “Blot heme” record matches the “Identifier” of the “Non-Proliferative” record, and the “ParentNum” of that record matches the “Identifier” of the “Diabetic Retinopathy” record. This structure dictates that “Non-Proliferative” will be a child of “Diabetic Retinopathy”, and “Blot heme” will be a child of “Non-Proliferative.” When the diagnoses lists are built from the database, they will have the multiple select box structure shown in Figure 19, and when the tree is built (see below), it will have the structure shown in Figure 21.

Table 1. Example records from the DiagnosesList table.

Identifier	ParentNum	Description	LineColor	FillColor	AltText	Changed	Deleted
2	0	Diabetic Retinopathy	0	0	NULL	-1	-1
10	2	Non-Proliferative	0	0	NULL	-1	-1
13	10	Blot heme	-4670860	1689827956	NULL	-1	-1

In order to allow the user to edit the list, Oxalis uses Java's JTree [27] object, which displays items in a manner similar to "Windows Explorer" or other file browsers. See Figure 21 for an example of the diagnoses table displayed in tree form. By defining a custom implementation of Java's TreeCellEditor [28] interface, we were able to use predefined methods to allow the user to edit the tree directly. When the user "double clicks" an item in the tree, a dialog is invoked which allows the user to edit any or all of the fields of the list item. See Figure 22 for an example dialog. The user may also click the "Add", "Remove", "Copy", and "Paste" buttons to the right of the tree to perform addition, deletion or duplication of a list element. The copy and paste operations function recursively – that is, copying a parent element automatically copies all of its children as well. The copy and paste operations are also bound to their standard Windows keyboard shortcuts (Ctrl + c and Ctrl + v, respectively). In order to insert or delete nodes from the tree, we used the predefined Java methods, found in TreeModel interface [29] and, more directly, in the DefaultTreeModel object [30]. Changes to the tree are replicated to the database table immediately (as soon as the user clicks the "OK" button on the dialog, or invokes the paste command).

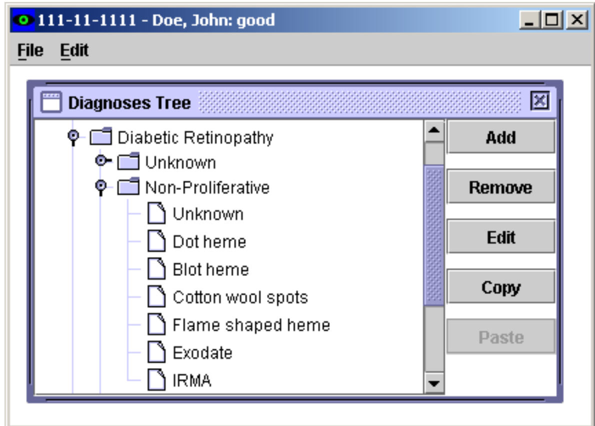


Figure 21. Diagnoses table in tree form.

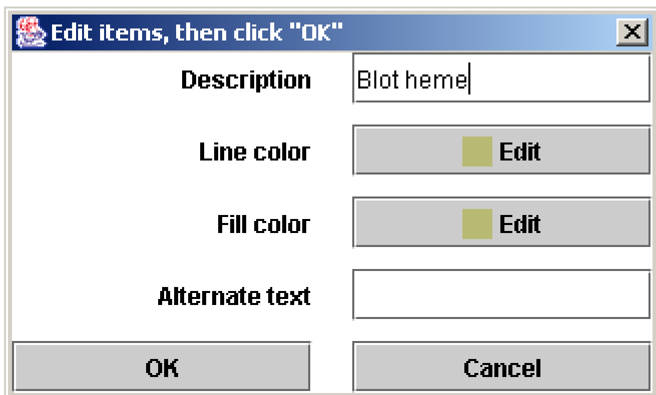


Figure 22. Diagnoses tree dialog.

However, allowing users to edit the diagnoses tree could pose a serious risk to the integrity of diagnoses. If changes to the diagnoses tree were reflected in annotations created prior to the change, it would enable a user to change an incorrect diagnosis by altering the annotation's text or removing it altogether. For this reason, once an item in the list has been used in an annotation, it will no longer be directly changed in the database (via an "update" or "delete" command) by Oxalis. Instead, the "changed" or "deleted" flag will be set (see Figure 20), indicating that the list item can no longer be used, but still allows previous annotations to refer to it. An entry will also be created indicating the date and time that the annotation was changed or deleted, as well as the new text of the annotation (if it was changed).

To transform the tree into the sequence of lists used during the process of annotating images, we first developed a custom subclass of Java's AbstractListModel [31]. AbstractListModel is a default implementation of the ListModel [32] interface, which is responsible for storing and providing all of the data used by a JComboBox [33].

When the JRE builds (or rebuilds) a JComboBox, it first invokes the getSize method of the list model to determine the length of the list The JRE then repeatedly invokes the getElementAt method to receive each element in the list, and passes them to the object responsible for rendering list items.

Our subclass of AbstractListModel, called "DatasetComboBoxModel", encapsulates a hash table. The hash table has two elements, a "key" and a "value". For the DatasetComboBoxModel, the key is a record from a preceding list, and the value is an array containing all elements of the current list. For example, from the records in Table 1, "Diabetic Retinopathy" would be a key in the hash table of the second DatasetComboBoxModel, and "Non-Proliferative" (as well as all other elements in the "Diabetic Retinopathy" list) would be the elements of the value array. Datasets are added to the model using the "addDataset" method, which takes the parent record ("identifier"), and child dataset as its two arguments. To switch to a different dataset, the "setDataset" method is invoked, with the parent key as its argument. This automatically causes the combo box to reacquire and render the list elements. When the user selects an item from the list, the list immediately to its right (the first child list) switches its dataset to the selected list item. It then directs its child list to switch datasets, and the change is replicated through all remaining lists in a similar fashion. See Figure 23 for the public methods of the DatasetComboBoxModel, as well as a brief description of them.

To optimize the update speed for editing the diagnoses lists and tree, the lists are built by retrieving the data from the tree and descending it in a breadth-first enumeration. This saves the system from making the numerous round-trip transmissions required to build the lists from the database. The database is only queried for the list during initialization. Thereafter, only update and delete queries will be performed to synchronize the user's changes.

This design, involving the diagnoses tree, lists, and editing and control components, completely eliminates the uncertainty text-based annotations would have introduced to diagnoses. It enables users to develop and deploy a single diagnosis structure across an entire institution, presenting a uniform "look and feel" to diagnoses and annotation of images.

```
public void addDataset(Object identifier, Object[] dataset)
```

Adds “dataset” to the hashtable, using “identifier” as the key.

```
public void setResetKey(Object identifier)
```

Set the key value to use when resetDataset is called to “identifier”.

```
public void resetDataset()
```

Reset the model to the default dataset, which is set using setResetKey.

```
public Object getResetKey()
```

Returns the key which is currently used as the default reset value.

```
public void setDataset(Object identifier)
```

Sets the currently displayed dataset to the one that has “identifier” as its hash table key.

```
public boolean hasDataset(Object identifier)
```

Tests whether this identifier references any dataset in this model.

```
public Object [] getDatasetKeys()
```

Returns all current identifiers from the hash table.

```
public Object getElementAt(int index)
```

Returns the object from array position “index” in the current dataset.

```
public int getSize()
```

Returns the number of elements in the current dataset.

```
public Object [] getDataset(Object identifier)
```

Returns the dataset referenced by “identifier” in the hash table.

```
public Object getSelectedItem()
```

Returns the currently selected item.

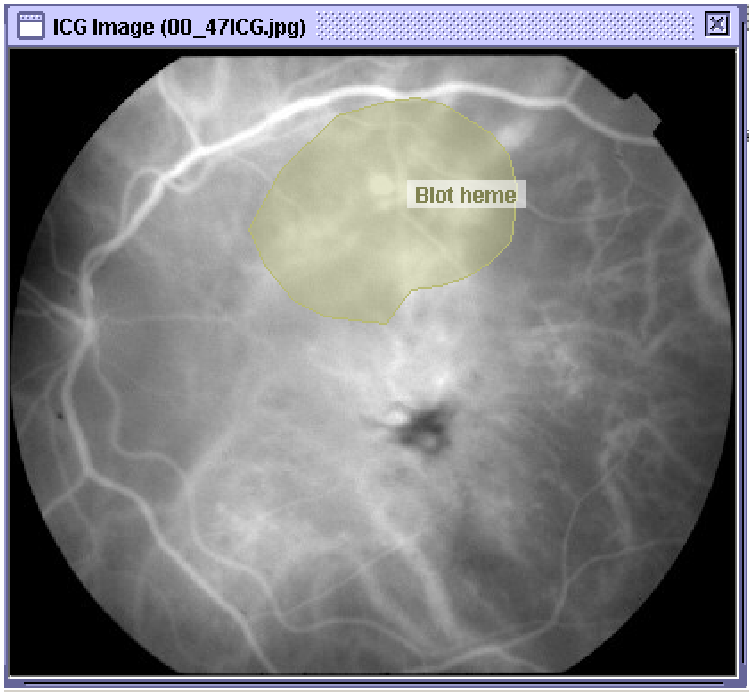
```
public void setSelectedItem(Object anItem)
```

Sets the currently selected item.

Figure 23. Public methods and comments for the DatasetComboBoxModel.

3.6 Export and Data Managers

In order to allow for future expansion of Oxalis, it was necessary to design a central object that could be queried to obtain all of the current "active" data, such as opened patient records, downloaded images, and annotations. The enables a developer to quickly accumulate the data his or her application will require, process it, and return it to Oxalis (if necessary) through predefined methods. In the future, it will also provide a single "checkpoint" for ensuring that an application has sufficient privileges to obtain the data it is requesting. Currently, the data manager is used by one object, which enables the user to export the current patient record, images, and annotations to HTML and JPEG images, for display outside of the system. See Figure 24 for an example of an annotated image in Oxalis, and exported to HTML.



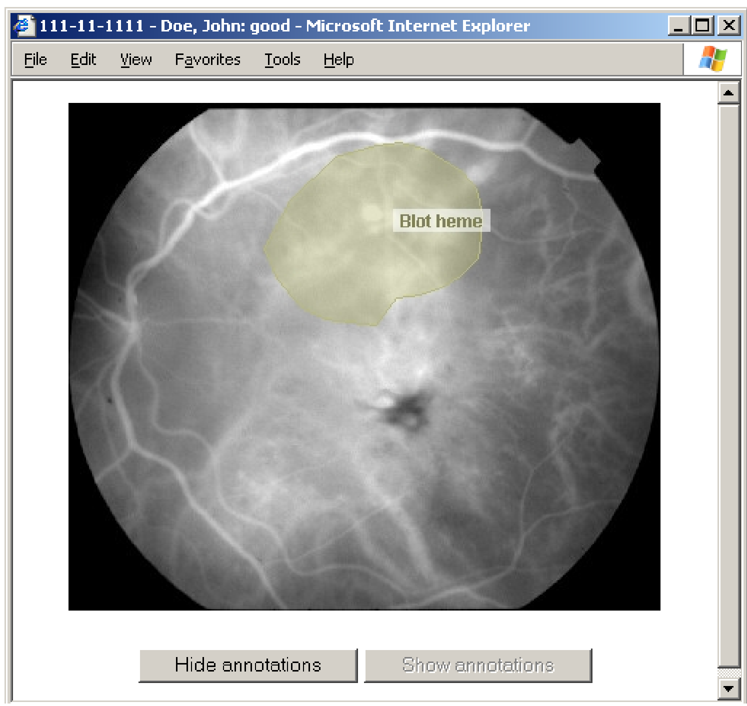


Figure 24. The top image shows an annotated image in Oxalis. The bottom image shows the same image after it has been exported to HTML.

Figure 25 shows the public methods of the DataManager class, the object designed for this purpose. Many of the methods are implementations of interfaces, such as the PatientListener interface (see section 3b) or Java's InternalFrameListener [34] interface. Through these interfaces, the DataManager is constantly updated with the most current data being used by the system. Developers can then invoke the getCurrentPanel method to obtain the most current image, including annotations, or the getCurrentPatient method to obtain the current patient information.

When the user selects to export an image to HTML, the system first queries the DataManager through the getCurrentType method to obtain the current image type (an image, an image group, or an image template). It then obtains the image's panel through the getCurrentPanel method, and the current patient record through the getCurrentPatient method. Using Java's BufferedImage class [35] and Sun's JPEG codec [36], the image and annotations are transformed to JPEG images. The HTML files are then created using a PrintWriter [37].

```
public Object getCurrentPanel()
```

Obtain the most current image panel activated by the user.

```
public int getCurrentType()
```

Returns an integer specifying whether the current panel is an image, an image group, an image template, or no known type.

```
public PatientRecord getCurrentPatient()
```

Returns the current patient information used by the system.

```
public void internalFrameActivated(InternalFrameEvent event)
```

Called by the system when an image is activated. This method is required for implementation of the InternalFrameListener interface. For the sake of brevity, the other six methods required for the interface have been omitted.

```
public void patientOpened(PatientEvent event)
```

Called by the system when a patient record has been opened. This method, is required for implementation of the PatientListener interface. For the sake of brevity, the other four methods required for the interface have been omitted.

```
public void drawStarted(ShapeEvent event)
```

Called by the system when the user has begun drawing an annotation. This method, is required for implementation of the ShapeListener interface. For the sake of brevity, the other six methods required for the interface have been omitted.

Figure 25. Public methods of DataManager.

3.7 Conclusion

The design and implementation of Oxalis successfully realizes the goal of enabling users to efficiently display, annotate, and share images. An XML initialization file to enable users to quickly change their source database and control the image processing capabilities of the system. To enable system components to be notified of changes to data records, and enabled developers to receive these notifications as well, Oxalis implements an event model similar to the one used by Java's AWT. To increase the ease with which Oxalis' image display capabilities can be maintained or enhanced, the system uses a strictly-specified structure of image display panels and a display panel factory. In order for the system to render annotations in a reliable, professional, and efficient manner, Oxalis was designed with an efficient painting algorithm and annotation display structure. By designing the annotation process to begin with a selection from a series of lists, instead of plain text entry, Oxalis eliminates uncertainty in diagnosis and redundancy in database storage. Finally, Oxalis aggregates the most current system data in a central object to aid developers in creating entirely new applications for use with Oxalis, and enable users to export their data to the World Wide Web.

However, there are still many improvements that could be achieved. This version of Oxalis is useable in a "trusted" environment, where machine-level authentication can be used to decide whether or not a user has access to the data, and extensions to the system are made freely available by developers. Unfortunately, it is not useable in an "untrusted" environment, where concerns as to the safety of data and/or program code exist. The modifications needed for Oxalis to function in such an environment will be the subject of the next chapter.

4.0 UNTRUSTED ENVIRONMENTS

The design and implementation of Oxalis discussed in the previous chapters is acceptable for "trusted" environments, where there are no concerns for the security of the users' data (due to the presence of firewalls, isolated subnets, Virtual Private Networking, etc.) or for the protection from unauthorized distribution of developers' code (due to a public licensing agreement, for example). The focus of this chapter is to describe the modifications to the design that would be required if Oxalis' environment were "untrusted", instead. In such an environment, Oxalis itself must provide some guarantee to both users and developers that their data and intellectual property cannot be modified or distributed without their permission.

We begin this discussion by examining the changes necessary to safeguard the users' data. We detail the steps necessary to protect the data from unauthorized access directly in the database, and those necessary to protect the data once it been downloaded by Oxalis. This includes placing a security layer between Oxalis itself and the data, to prevent a malicious developer from designing a component expressly to distribute users' data.

We then examine the steps necessary to provide some measure of security for the intellectual property of developers. This also involves protecting the executable code in the database, and in Oxalis. A brokerage architecture for obtaining code from distributed sources in a secure manner has previously been designed by researchers at the University of Pittsburgh, and will be discussed. We will also discuss the security measures that can be taken to prevent unauthorized users from executing code, or from obtaining and distributing it.

4.1 Protecting the Users' Data

Protecting the users' data in an untrusted environment is of the utmost concern. If the records in Oxalis contain Protected Health Information, or data that would allow a patient to be identified and which relates to the past, present, or future health of the individual, then, in order to be in compliance with the Health Insurance Portability and Accountability Act of 1996, an institution must be able to demonstrate that the data is safe from unauthorized access. If the networking environment for Oxalis cannot provide the guarantees necessary to demonstrate this, than Oxalis must do so itself. In order to accomplish this, the data must be protected at three points: in the database, during transmission, and once it has arrived in Oxalis. The first and last of these points will now be discussed in detail. It will be demonstrated that security during transmission follows from securing the database.

4.1.1 Protecting the Database

In order to safeguard the data, the database itself must be strongly protected. In the current system, users that can read the Oxalis initialization file can quickly determine all of the parameters necessary to connect directly to the database, which would allow them to read or modify any record contained therein. For an untrusted environment, this is unacceptable, as it allows any user that either has been authorized to use Oxalis or has gained control of a machine with Oxalis installed to compromise any record in the system. The solution to this problem involves two main components. First, a modification to the Oxalis architecture must be made, placing a server between users and the database, so that the database can be isolated from direct traffic; second, the data must be encrypted for storage and transmission.

If users can directly access the database over the network, no other security measures can fully safeguard the users' data from each other. Therefore, we must modify the original architecture of Oxalis to include a server, and become a client-server-database distributed architecture, as opposed to the untrusted form, where the server is the database itself. The revised architecture is shown in Figure 26. Under this architecture, clients log in and authenticate with the server, instead of the database. They then submit queries as command strings or messages to the server, which first checks whether or not the client is authorized to obtain the data, and then performs the query, returning the result to the client. If the database is placed in an isolated network (accessible only to the server), it can be shielded completely from any attack that does not originate either at the server, or locally (by logging in to the machine the database resides on). Additionally, only the person responsible for maintaining the server needs to know the username and password required to connect to the database.

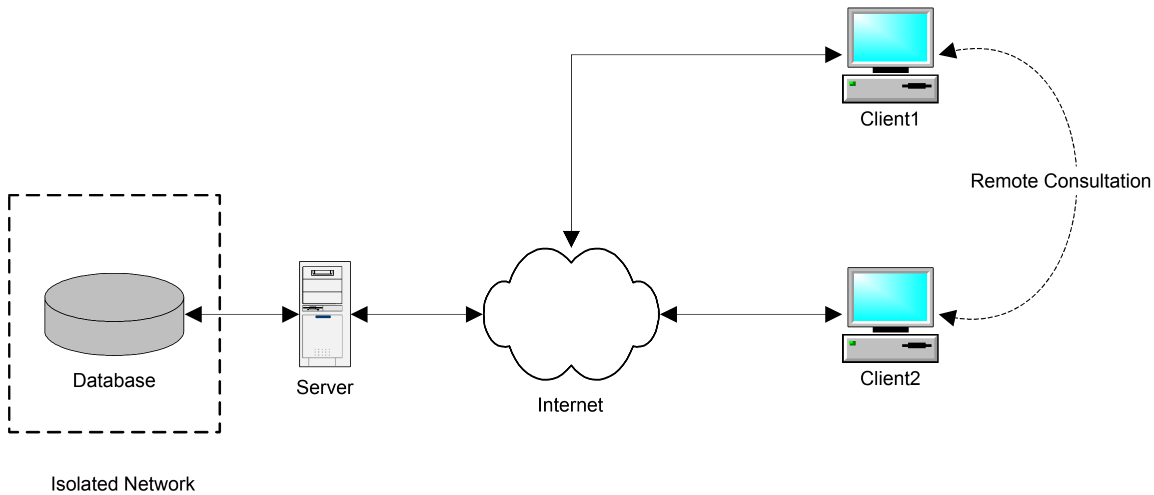


Figure 26. Modifications to the high-level architecture required to ensure the safety of the database.

However, by either compromising the server through a replay attack, in which known login credentials are used to mimic the command sequence of Oxalis, or intercepting a data transmission once it has left the server, a malicious user could still gain access to and compromise users' data. In order to prevent this, data must be encrypted prior to transmission by the server and/or storage by the database. If data are encrypted and decrypted by Oxalis when it leaves or arrives at a client computer, then interception during transmission or by compromising the server is only a viable option for a user that has access to the encryption algorithm and cryptography key used by Oxalis. While a Virtual Private Network or Secure Socket Layer communications assure data security during transport, it would not prevent a user that has compromised the server from being able to receive fully decrypted data. Therefore, Oxalis must perform the encryption and decryption itself. Fortunately, the most current release (1.4) of the Java Runtime Environment includes the Java Cryptography Extension [38], which enables developers to use the Data Encryption Standard [39], the Advanced Encryption Standard [40], the RSA encryption algorithm [41], and numerous other algorithms to encrypt and decrypt data.

However, the process of encrypting and decrypting the data will still result in decreased performance of the system. To determine how detrimental the effects would be, we tested the time required to open and read an image data file versus the time required to open, read, encrypt, and decrypt the data file. Three file sizes were used, one each of 31 kilobytes (KB), 122 KB, and 1.38 MegaBytes. Each image file size was tested 1000 times. The parameters used for encryption were: DES algorithm, Electronic Codebook mode, and PKCS #5-style padding. As expected, the unencrypted form clearly outperformed the encrypted form. For the 31KB file, the process of reading the file into memory took .762 milliseconds, on average, whereas the time to read the file, encrypt it, and decrypt it took 32.944 milliseconds. For the 122KB file, reading the file took 2.532 milliseconds, on average, and reading, encrypting, and decrypting took 171.966 milliseconds. For the 1.38 MB file, reading the file into memory took 81 milliseconds on average, whereas reading, encrypting, and decrypting it required 1.891 seconds. A chart of these results can be found at the end of this chapter, as Figure 34.

4.1.2 Protecting the Data Inside Oxalis

Securing the database and encrypting the data would both be nearly meaningless if a user could access other users' data directly in Oxalis, as they can in the version designed for trusted environments. In that version, if a user has access to Oxalis, or to a computer that has Oxalis installed, he or she can access any patient, image, or annotation record in the database.

In order to guard against this, Oxalis must include the capability to create user accounts and roles. User accounts are unique identifying information for each authorized user of the system, by which the system can authenticate them. The identifying information can be anything from a username and password to a fingerprint or retinal scan. Roles are groups of user accounts that have similar access privileges. Examples of roles would include “clinicians”, “residents”, and “administrators”.

Users must then be allowed to specify permissions on records that they create, detailing which users and roles have access (read, write, list) for them. These permissions must be checked at the server, prior to transmitting data. If the data were transmitted and then filtered, a malicious user could more easily disable the filtering algorithm, and gain access to the entire record set.

The Java Authentication and Authorization Services (JAAS) extensions, which have been included in version 1.4 of the Java Runtime Environment (JRE), could be used to implement these changes [42]. JAAS enables developers to specify the method for obtaining a user’s identifying information and authenticating that user in a “pluggable” fashion. The authenticating agent is specified in a configuration file, and loaded at run time, which enables administrators to switch authentication methods without recompiling the source code. The JAAS distributed with Sun’s JRE implements username and password authentication, Windows New Technologies authentication, public key authentication, and several other authentication methods. Developers use a well-defined interface to obtain identifying information from users and validate that information with a datastore. These methods would solve the first portion of the problem, ensuring that only authorized users can access the system.

There are two possible architectures for specifying permissions on record sets. The first architecture uses Java’s predefined security framework. In this framework, security restrictions and permissions are defined by subclasses of the Permission [43] object. Subclasses of Permissions would therefore need to be created, describing all of the critical operations that can be performed on data records. The default extensions to the Permissions object enable users to specify different file, socket, and service permissions, and it may be possible to modify one of these to serve as the basic permission to control data access in Oxalis. Permissions are checked by an object called the SecurityManager [44] when a critical system operation (reading a file, opening a socket) is performed, or when an object explicitly asks that a permission be checked. The data source for the SecurityManager in Java's security framework is the Policy [45] object. However, the Policy class is abstract, and the only default implementation provided by Sun uses a file-based datastore to specify access. This would be unacceptable for the large number of permissions required by the system, as individual annotations could have several different users, roles, and access levels assigned to them. Therefore, a subclass of Policy would need to be designed to query the database for its object permissions. Once a custom Policy and custom subclasses of Permission were designed, checking object-level permissions would be a matter of invoking the appropriate methods in the SecurityManager on the Permissions object at the server. As the SecurityManager runs at a lower layer of the runtime environment than user code, this would be the most secure method to safeguard users' data. The Java Runtime Environment will not allow code to alter or even access the installed SecurityManager unless 1) the code comes from a trusted source, and 2) the code has a special system-level permission to do so.

The second possible architecture for specifying permissions on record sets uses stored procedure calls in the database to control record access. The server checks with the database to ascertain the access level a user has for a given dataset and filters the results accordingly, returning the remainder to the client. However, this method would result in the security mechanism running at the same layer as users' code, making it much easier to defeat. A malicious developer could much more easily create an object to disable this security architecture than the previous one.

Once either of these architectures are fully designed, all that remains is the design of user interface components to allow users and administrators to specify permissions. This would require sending command strings to the server to obtain the list of accessible users and roles, and the current security status of the object, and then to update those lists, encrypt them, and relay them to the server for processing and storage.

Finally, socket, file, and service permissions would need to be developed to prevent the server or client software from transmitting or storing users' data in an unauthorized fashion. This is especially important because the system is intended to be extensible, involving third-party developers or other component sources. A malicious developer could design a component that would appear to perform useful work, such as displaying the negative of a grayscale image, but would also transmit the image data to a location outside of the institution's network for further dissemination. This could be prevented to some extent by fully testing new components before deploying them on an institutional basis, but further preventative measures would be necessary to completely guarantee the safety of users' data. The latest revisions to Java's SecurityManager enable an administrator to control the socket and file permissions a component has on a component-by-component, source-by-source, and/or user-by-user basis, and using these permissions to effectively control the access system components have to the outside world would also be required.

4.2 Protecting Developers' Intellectual Property

In cases where the code and intellectual property of developers is not released to the general public or is sold in source form to an institution, it becomes important to offer a means to protect this property from unauthorized distribution. Failure to do so will result in decreased income for third-party developers or loss of intellectual property entirely, which would discourage others from developing extensions to Oxalis. However, in the course of securing the code, the interoperability and extensibility of Oxalis must not be compromised – components must be able to search for and obtain any data or processing function they require, provided they have permission to do so.

If all system components and additions are installed on each client's computer, the potential for piracy becomes high. While various copy protection algorithms and methods, such as Digital Rights Management [46] and executable encryption [47], have been developed, none of these has proven to be one hundred percent reliable without disabling the user's computer. The backlash from users against these methods has also been strong, especially in cases where the copy protection disabled devices it was never intended to influence [48].

The solution to this problem involves three main concepts. First, a brokerage architecture must be designed so that either the user or a system component can search for and request a remotely-stored object or method, regardless of the language the object is implemented in. Second, there must be a method to download the remotely-stored object, or an interface to it, and begin executing the desired methods. Third, there must be a method for a downloaded component to request further processing from other remotely-stored components. At each stage, the security of both remotely-stored objects and client data must be guaranteed.

4.2.1 Brokerage Architecture

Researchers at the University of Pittsburgh have developed a distributed, secure, interoperable brokerage architecture known as Pegasus. This architecture enables a service or application provider to register methods and processing capabilities they wish to make available to clients with a central index. A client or object can then search the index for an object that implements a set of desired methods or performs a desired operation. If an appropriate object is found, the index server aids the provider in connecting to the client to deliver the object in encrypted form. The client then petitions the index server for the appropriate decryption key and decrypts the object. A diagram of this architecture is shown in Figure 27.

While this architecture does enable a client to securely search for and obtain an object performing desired functionality, it does not specify how an remotely-stored object can be instantiated on the local machine. This is the subject of the next section.

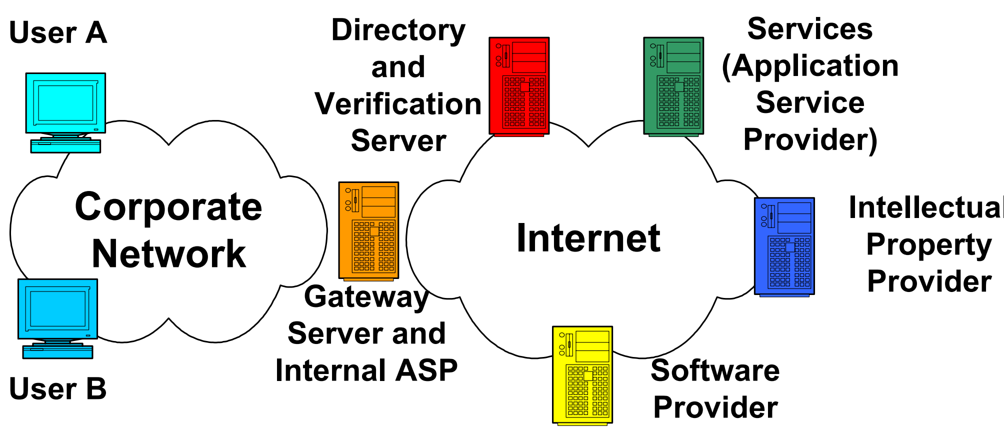


Figure 27. Pegasus Architecture.

4.2.2 Object Instantiation

Once the code for an object has been downloaded by the system, the system must have a way to instantiate, assign data to, and execute methods of the object, without first needing to write the object to disk. For objects implemented in Java, an extension of Java's SecureClassLoader [49] and reflective library [50] can be used to accomplish these tasks. By default, Java instantiates a ClassLoader as part of the virtual machine, to load objects into memory as they are accessed. The main methods used by the ClassLoader to locate and load objects are *findClass*, which converts a class name to an instance of the object's class, and *defineClass*, which transforms an array of bytes representing Java byte code into a Class [51] object of the appropriate type. The SecureClassLoader is an extension to the ClassLoader architecture, which enables the runtime environment to determine the access rights a code source will have. Once an array of bytes has been resolved into a Class object by the ClassLoader, it is possible to instantiate the object directly using the *newInstance* method, which returns a reference to the newly-contructed object, or by using the Constructor [52] class. The Constructor class is a member of Java's reflective library. Its name refers to the method normally used to directly instantiate an object, which in C++ and Java is called the "constructor method." Java's Contructor class enables a developer to search for and access the constructor methods of an object without knowing anything about the object at compile time, and use these methods to instantiate the object. Note that the byte code is never written to disk; it can be loaded, resolved, and instantiated entirely in memory, which makes it extremely difficult to obtain and/or distribute the code via unauthorized means.

Using a subclass of SecureClassLoader, as well as the Java Cryptography Extensions, it is possible to download, decrypt, instantiate, and execute a remotely-stored object, if the object was written in Java. However, there are a large number of applications that could interoperate with Oxalis, but have already been implemented in a different programming language, such as C++ or Visual Basic. These objects pose a special challenge for code security, as they are generally installed in binary executable code, which by itself would be sufficient to distribute and run the application.

To solve this problem, the Common Object Request Broker Architecture (CORBA) could be used. This architecture enables an application to execute methods on an object that resides on a remote server. Under CORBA, objects publicize a “stub”, an interface containing all of the public methods other objects should be allowed to access. When an object invokes one of the methods in a stub, the arguments are seamlessly passed to the host machine over the network, where they are processed, and the results are returned to the requestor. This means that the binary code and data processing reside on the remote machine. Only the stub and result set from the operation are passed to the client. This guarantees the safety of the binary code, since only the byte code for the stub is transmitted. However, if too many clients attempt to access the same object at the same time, the host computer may become overburdened. Currently, CORBA libraries exist for C, C++, Visual Basic, and Java, making this an ideal architecture to use for binary code blocks that are not written in Java.

In some cases, it is necessary to establish bidirectional communication with a remotely-stored object. An example of bidirectional communication would be the client application invoking a method on the remotely-stored object, which in turn causes the remotely-stored object to invoke a method on the client application. Generally, it should be possible to eliminate the need for bidirectional communication through interface and return type definition, but, in cases where it cannot be avoided, it is important to deliver the relevant client data and methods as a newly-created data interface instead of passing a reference to the entire client application. If the client application is passed, a remotely-stored object provider with knowledge of the Application Programming Interface of the client application could more easily obtain unauthorized data. Using the data interface, on the other hand, the client application can specify exactly which data elements the remote-stored object has access to (through the inclusion of “getDataElement” methods), and what bidirectional methods are available (through the inclusion of “setDataElement” methods).

It would be inefficient to download, decrypt and instantiate an object every time it was required. For most applications, if the remotely-stored object could be downloaded into memory and instantiated once, and then "looked up" locally each time it was required, it would greatly increase efficiency. In order to accomplish this, an entirely new object (called the ClassRegistry) will now be presented.

4.2.2.1 <u>The ClassRegistry Object.</u> The ClassRegistry exists to provide a reference to previously-instantiated objects. This is important for two reasons: first, it enables objects to first ascertain whether a remotely-stored object has previously been instantiated, and second, it ensures that the remotely-stored object will not go out of execution scope and be garbage collected by the runtime environment. The current "trusted environment" version of Oxalis uses a ClassRegistry to maintain references to single-use objects. We will begin by discussing the current form and the functionality it provides, and then move on to discuss enhancements to it that would enable it to function effectively in an untrusted environment.

The public methods of the ClassRegistry object currently used by the system are shown in Figure 28. If an object wishes to register itself with the ClassRegistry, it passes the class name it wishes to register under as the "className" argument, and itself as the "classObject" argument, to the registerClassObject method. The ClassRegistry will then check to make sure that the object is in fact of the appropriate type (assignable from the "className" argument), and, if the check passes, store a reference to the object in an index. If an object wishes to obtain a previously-registered object, it invokes the "getClassObject" method with the appropriate class name, and if the class name is found in the index, the object that last registered with that name will be returned.

```
public static void registerClassObject(Class className, Object classObject)
```

Enables an object to register itself by Class. Once the object is registered, it will be returned when another object invokes getClassObject on its class name.

```
public static Object getClassObject(Class className)
```

Queries the registry for the appropriate class, and returns it if it is found.

Figure 28. Public methods of the current ClassRegistry.

This design provides a middle ground between a fully static object (one with only static methods and data elements) and a fully instantiated object (one without any static methods). Objects can query the registry for an appropriate class to perform a particular function, assign state variables to the object, and then invoke methods on the object, without needing to have the object passed in via a constructor or as an argument to a method. Additionally, many objects can register at different times under the same base class or interface, and only be returned if they are the most recent object to register. This is useful for situations when several different components wish to perform a similar operation, but only if they visible. An example of this would be a progress bar for data upload. Multiple objects may wish to register as maintaining a progress bar, and allow the component that performs the data upload to manipulate the progress bar. However, the component that displays the progress bar for uploading image data will most likely not wish to be notified when binary data for code is being uploaded, for example. Using the ClassRegistry, an object can register itself as the ProgressBarManager (for example) immediately before displaying its progress bar. Therefore, when the code upload progress bar is about to be displayed, its manager will overwrite the registry entry for ProgressBarManager, and prevent the image upload progress bar from being notified.

In order to provide support for the distributed, interoperable code sources in the untrusted environment, several additional functions need to be added to the ClassRegistry. First of all, it must implement the same query functionality as the index server in Pegasus. It would be unrealistic to expect code to first query the index for desired functionality, and then become aware of the class name of the objects. Second, the ClassRegistry must provide security mechanisms to ensure that objects have permission to access each other in the desired manner. Third, the ClassRegistry would need to be modified to support multiple objects of the same class type, so that one remotely-stored object could not accidentally overwrite another.

Using Pegasus, Java's SecureClassLoader, CORBA, and a modified ClassRegistry, the system could now download and instantiate an object while guaranteeing the security of service provider's intellectual property. It could also access the object without downloading it, if it has already been downloaded once in this execution instance. However, there are many cases where one remotely-stored application may wish to obtain special processing from another. To fulfill this goal, it is necessary to ensure that objects cannot gain access to data they were not intended to have. For instance, if the first remotely-stored object is allowed to access all of the annotations to an image, but a second is only supposed to access a single annotation, it would be hazardous if the way the two objects interacted involved passing the entire list of annotations back and forth. Therefore, a series of interfaces, describing exactly what data a remotely-stored object will need in order to perform its functions, as well as what data it is capable of providing, need to be designed.

4.2.3 Interoperability Interfaces

A balance must be achieved between the desire for components to be able to interoperate with each other, and the need for security of the users' data. If data is too freely disseminated, the risk for alteration or corruption, whether through malicious or accidental means, becomes high. On the other hand, if data is too tightly controlled, interoperability of components would be impossible, as one component could not determine or provide the appropriate data to another.

To achieve this balance, each of the remotely-stored objects that wishes to interoperate with others will be required to publicize an interface containing all of the critical operations, as well as the data required to perform those operations. Interfaces may implement a security mechanism that passes custom Permission objects to the SecurityManager, to ensure that data is not being obtained in an unauthorized manner. These interfaces can then be checked by administrators before agreeing to use the object, to ensure that each of the methods and data elements are actually required for the object to function, and that it is not providing sensitive data to other objects indiscreetly.

Once the interfaces have been declared and approved, they can register with the ClassRegistry. Other service providers can be notified of the capabilities of the new interfaces, and, when their components are loaded into the system, can use either the ClassRegistry or the index server to locate the appropriate object.

4.2.4 Example

This section presents a sequence of block diagrams with descriptions that detail the process of loading, instantiating, and establishing interconnectivity between remotely-stored components. We begin with Figure 29, which shows a simplified view of the system at startup.

Note that for the purposes of this example, the server and image database, as well as the index server for Pegasus, have been removed from the diagrams.

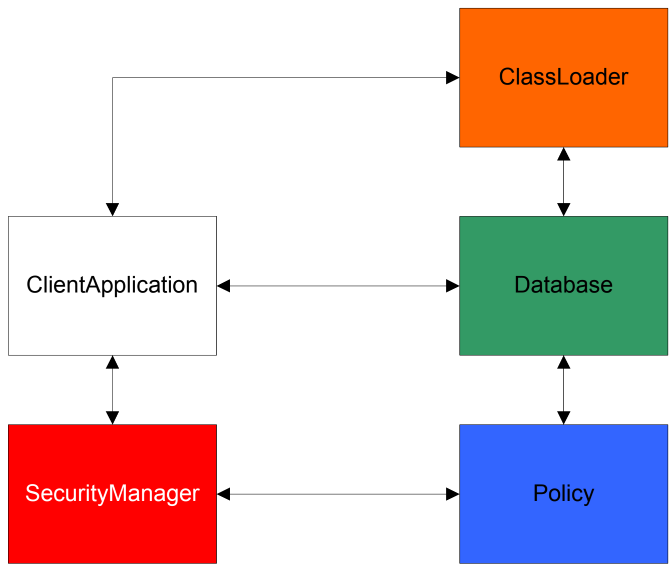


Figure 29. Simplified view of the system at startup

This figure shows the ClientApplication ready to begin loading plugins. The SecurityManager will handle all security checks by passing them to the Policy, which will check the permission in the Database. The ClassLoader will retrieve plugin byte code from the Database, and instantiate it for the ClientApplication. At this point, the ClientApplication contains all relevant data for the application.

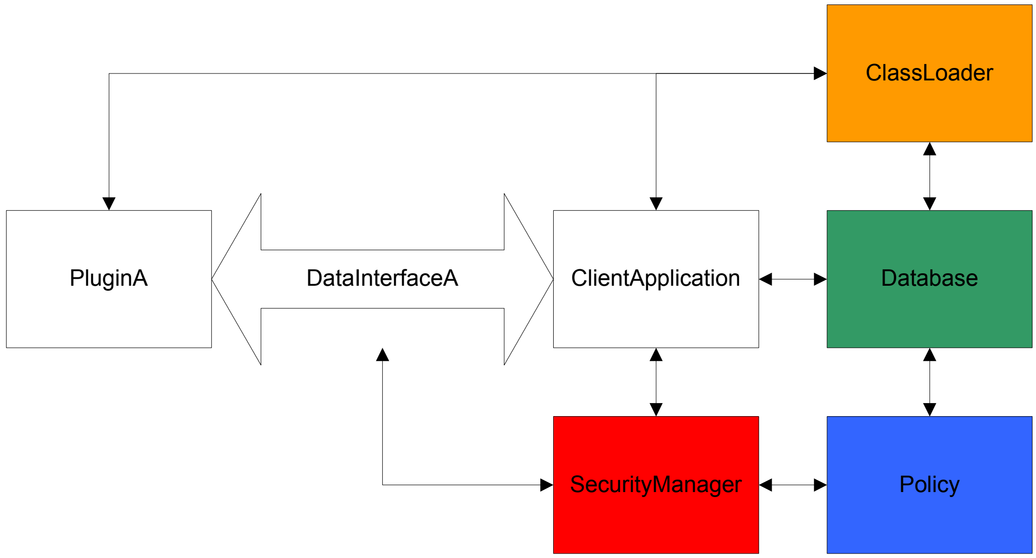


Figure 30. First remotely-stored component has been loaded.

Figure 30 shows the ClientApplication, having loaded its first remotely-stored object (PluginA). To do this, it called the ClassLoader, which loaded PluginA's byte code from the Database (after finding it in the Pegasus index). Once PluginA is loaded, the ClientApplication gives it a DataInterface (DataInterfaceA) which contains "getYyy" and "setYyy" methods to access the data PluginA will require. DataInterfaceA will reference the SecurityManager any time PluginA attempts to invoke a method, to check whether or not PluginA has permission to do so.

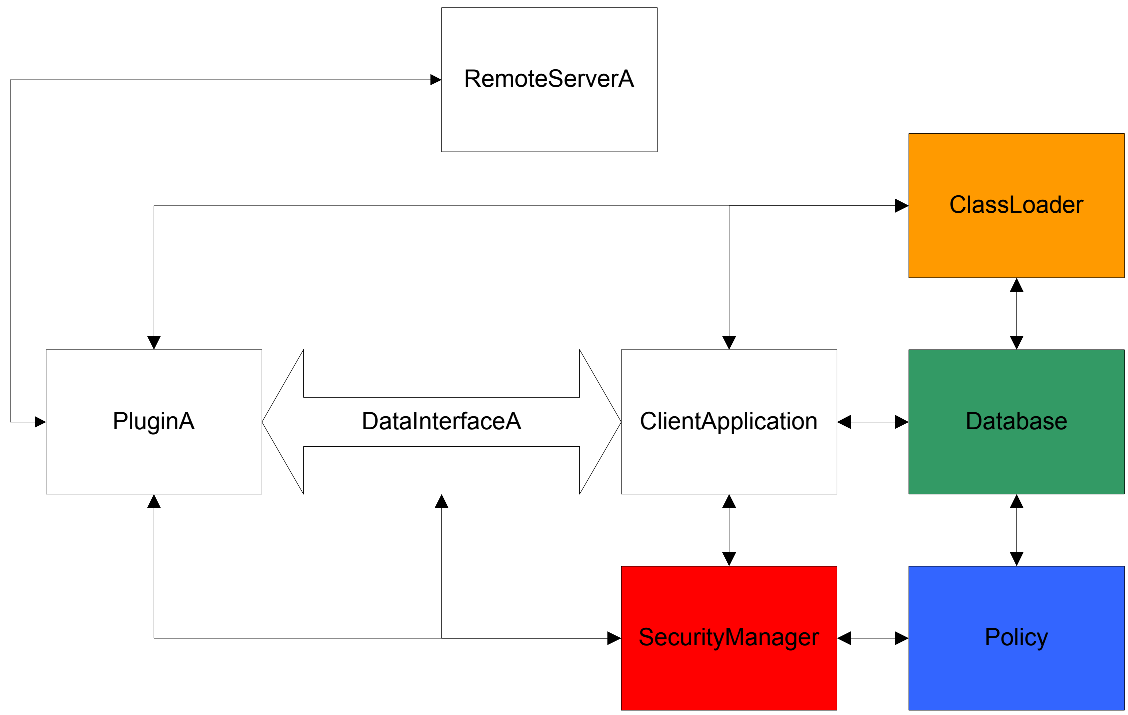


Figure 31. A remote object loaded through CORBA

Figure 31 shows a remote object (PluginA) which cannot safely be stored or loaded by the ClientApplication (because it is a binary instead of byte code, a different language, etc.) In this case, the object loaded by the ClientApplication does not perform any useful computations. Rather, it is a "stub" file, which accesses a RemoteServer (RemoteServerA) using CORBA. RemoteServerA performs the processing and computation, and returns the result to PluginA, where it is passed back to the ClientApplication (through DataInterfaceA). When PluginA attempts to establishes its connection to RemoteServerA, the SecurityManager will check to make sure it has permission to do so.

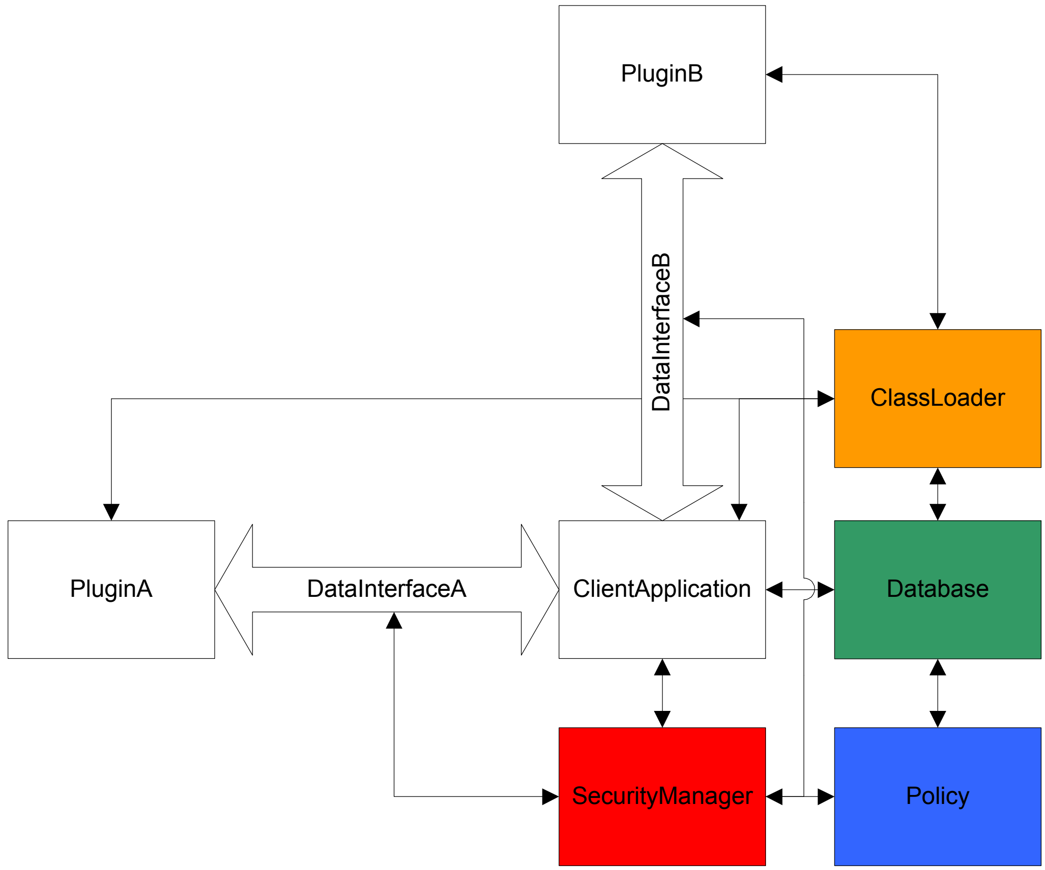


Figure 32. A second remote object has now been loaded by the system.

Figure 32 shows a second plugin (PluginB) loaded by the ClientApplication. Like PluginA, it has a DataInterface (DataInterfaceB) which gives it access to the ClientApplication data it needs. This DataInterface also checks necessary permissions with the SecurityManager.

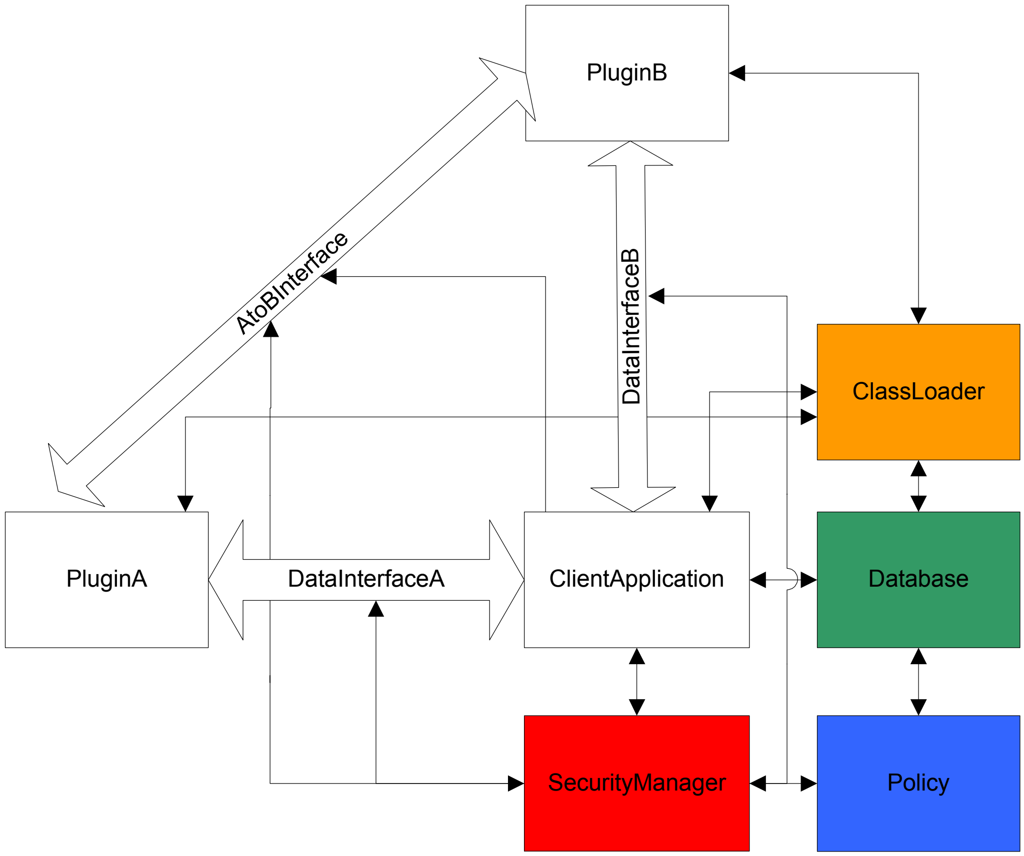


Figure 33. The two remote objects establish interconnectivity.

Figure 33 shows PluginA and PluginB connected directly through AtoBInterface. To accomplish this, one of the two plugins requests the interface from the ClassRegistry. The requesting plugin provides the AtoBInterface, which ClassRegistry passes to the other plugin. This allows A and B to communicate directly, instead of passing data through ClientApplication. Data security can be guaranteed by the SecurityManager, which oversees the entire transaction.

4.3 Results Of Testing

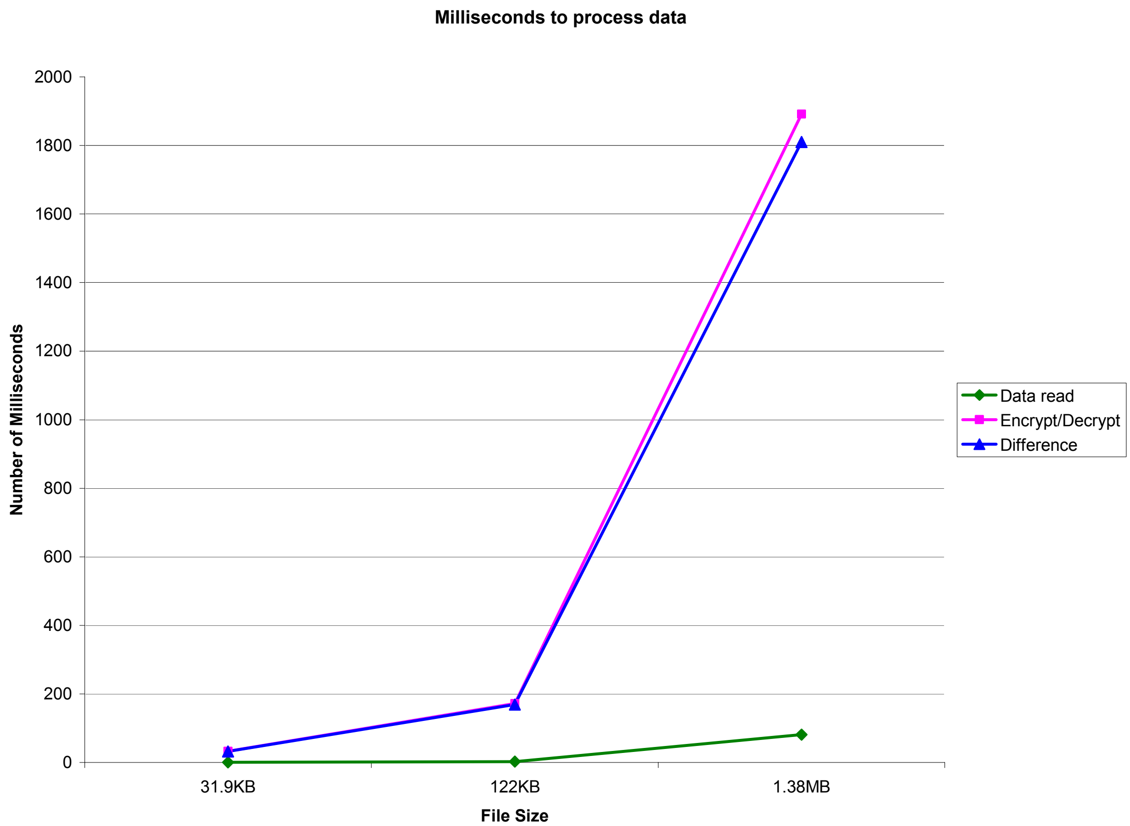


Figure 34. Chart of Encryption Test Results.

4.4 Conclusion

This chapter has presented the steps necessary to enhance Oxalis so that it could function effectively in an untrusted environment. We have demonstrated the ability to protect the users' data from both unauthorized users and developers. We have also detailed an architecture which allows system components to be distributed so that they do not need to be installed locally on users' computers. This greatly reduces the risk of unauthorized distribution of developers' intellectual property.

5.0 CONCLUSION

Oxalis represents a step forward in the workflow of ophthalmic photographers and clinicians. Instead of separating the photograph from the observed pathologies and diagnosis, Oxalis links the two directly. It leaves no "guesswork" for clinicians in reviewing a case file – the pathology is presented exactly where it was drawn. It also allows for easy transfer of information and remote consultation, as clinicians can connect to multiple Oxalis servers scattered in different physical locations.

The architecture of Oxalis was designed to maximize the efficiency of the system for users, and minimize the amount of maintenance they would need to perform. A database was created to hold all image and annotation data, enabling users to share clinical information regardless of physical locality. An XML initialization file was implemented to enable users to switch their source database and control image display parameters without needing to recompile the source code. The diagnoses lists were designed to eliminate the redundancy of typing the same description multiple times and the ambiguity of free text descriptions. The diagnoses tree was designed to enable users to edit the lists in an efficient and familiar manner. Image groups and image templates were implemented to enable users to group and hyperlink images logically.

The other goal for Oxalis was to design it as an extensible system, in which developers can easily integrate new components. An event model similar to the one used by the AWT was implemented so that components can receive notification of data events from the system. A specification for image interpretation and display panels was developed to enable new image formats to be implemented and integrated with the system. A central query point was designed to enable new components to obtain the most current system data.

The above system was designed for trusted networks, where machine and network security can guarantee the integrity of users' data and developers' intellectual property. In order to protect the system in untrusted environments, a number of steps will need to be taken, including the introduction of a server in addition to the clients and database, the development of a security protocol, through either Java's security framework or a custom method, and the development of an architecture to enable the system to load and execute remotely-stored objects securely.

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