Friendly "ImageJ":
A pedagogical tool for teaching image-processing programming in Java

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***Abstract*:**

Image processing can be taught very effectively by complementing the basic lectures with computer laboratories where the participants can actively manipulate and process images. This offering can be made even more attractive by allowing the students to develop their own image processing code within a reasonable time frame. After a brief review of existing software package that can be used for teaching IP, we present a system that we have designed to be as “student-friendly” as possible. The software is built around ImageJ, a freely available, full-featured, and user-friendly program for image analysis. The computer sessions are given in alternation with the lectures; typically, a three-hour session at the end of every chapter. The sessions are in the form of assignments that guide the students towards the solution of simple imaging problems. The starting point is typically the understanding and testing of some standard image-processing algorithm in Java. Next, students are asked to extend the algorithms progressively. This constructive approach is made possible thanks to a programmer-friendly environment and an additional software interface layer that greatly facilitates the developments of plug-ins for ImageJ. Taking into account the fact that our students are not experienced programmers (they typically do not even know Java), we use a “learn by example” teaching strategy, with good success.

Keywords:

Teaching image-processing, Programming image-processing, Computer laboratories, ImageJ, Java.

I. INTRODUCTION

Because of the widespread use of imaging, there is an ever pressing need to train engineers that are proficient with this new technology. This trend is likely to continue as the cost of imaging devices (digital camera, scanners, etc) keeps declining, and as the power of personal computers keeps increasing, making sophisticated image processing algorithms available to a larger base of users and increasing the potential number of applications.

Many universities are meeting this demand by offering a basic course in image processing (IP)—typically, a two semester class—that covers all the standard techniques. While image processing comes in many gradations, it is typically a topic that is perceived as being rather theoretical. Image processing is indeed a subject that lends itself quite naturally to a rigorous, mathematical treatment. The mathematics are not difficult but the notation can be intimidating because of the multiple sums and indices. On the other hand, image processing is also a very practical discipline; it is extremely motivating for students to see that the formulas are easily translated into algorithms, often with dramatic visual effects.

Since engineering students are often more interested in applications than in pure theory, there a strong incentive for instructors to complement the basic lectures in IP with computer laboratories. A number of initiatives in this area have demonstrated that students gain a lot in their understanding [1]; they develop in-depth understanding and have a better retention of theoretical material [2]. The students become motivated to study theory if they can experiment with algorithms [3] and visualize the results. Interactive software is generally perceived as a useful tool for complementing textbooks [4] [5].

The purpose of this paper is to discuss some of the important issues relating to the use of computer sessions in IP and to present some practical and cost-effective solutions for implementing these ideas in the classroom. It is organized in such a way that we move from the global to the more specific. In the first part, we discuss the advantages of hands-on experimentation with IP and identify the key points that need to be taken into account to make such an approach successful. We then briefly review the software solutions (both commercial and freeware) that are currently available for teaching image processing. In the second part, we get more specific and describe a system (IPLab) that was developed by us at the Swiss Federal Institute of Technology in Lausanne (EPFL) and that is made freely available to the academic community. While our initial motivation was to provide a system where the participants would actively manipulate and process images, we took the challenge further so that we would have the students write their own image-processing code down to the pixel level. Of course, we also wanted to give them the benefit of a user-friendly interface and of a software platform that they may extend to perform sophisticated image processing tasks. Even though a rudimentary knowledge of the Java syntax is required (which can be acquired in a one-hour lesson), we should emphasize that this knowledge comes at essentially no effort from the part of the student and that the laboratories require little programming skills. There is no need to teach the students how build a complete object-oriented applications [6]. Rather, they are invited to understand some example code, which they then modify to achieve their goals.

II. HANDS-ON IMAGE PROCESSING

Even when the lectures include visual demonstrations of image-processing algorithms, students are often passive. Learning the mathematical concepts can be facilitated with hands-on experimentation. The first level of involvement is to apply the algorithms to real images and to see the results. The second is to take part in the programming itself and to truly experience how formulas translate into algorithms.

2.1 Image processing by direct image manipulation

The usual way to get the students involved is to provide a convivial computer environment that allows them to try out different algorithms and to visualize the results. The key points here are the following:

- Basic manipulations to illustrate and reinforce the theoretical concepts treated in the course. Visual experimentation with different sets of parameters.
- Use of practical examples to demonstrate image-processing applications. Chaining of simple modules.
- Need for a user-friendly interface to facilitate interaction with the computer. Production of results that are visually appealing.

Such experimentation can be achieved easily by using standard image-processing software.

2.2 Programming image-processing algorithms

Once the students are accustomed to manipulating images, the challenge is to have them program simple image-processing algorithms. Our key requirements for this more ambitious level of involvement are as follows:

- The best way to truly understand an algorithm is obviously to code it and to test it. Students should get the opportunity to implement the most representative algorithms.
- The exercises should be accessible to inexperienced programmers (very basic knowledge in one language, e.g., C). The assignment should concentrate on image-processing issues alone. To facilitate programming, we propose a “learning by example” approach: students receive the source code of a basic image-processing task and are asked to extend and/or complete the algorithm.
- The students should not have to worry about data types. The code should be as generic as possible.
- The programming should be simple and robust. The graphical user interface and input/output task should be provided to avoid spending time on what is non-essential to our purpose (i.e., teaching image processing).
- The edit-compile-execute programming cycle should be short to see immediate effects on the images when modifying the code.

The two traditional ways to practice image processing are through the use of a low-level language (such as C) or a high-level language (such as Matlab). The low-level language offers the advantage of computational speed, an important factor when dealing with images, but students waste a lot of time with basic input-output operations (reading files, data types, memory allocation, accessing pixels and displaying images) and rapidly lose their enthusiasm. A high-level language, on the other hand, offers a rich functionality with a large palette of imaging routines, but tends to hide many important aspects of the algorithm.

III. OVERVIEW OF AVAILABLE PACKAGES

We now proceed with a brief review of the software solutions that are presently available to instructors. There has been a substantial effort by members of this community to create didactic tools for teaching image-processing; a number of systems have been described in the literature and part of them are available on the Internet (cf. the links we are providing in our reference list). Special sessions at conferences and workshops have been organized on this topic [7] [8]; a recent review on computer vision education is also available [9].

The choices of the instructor are usually oriented by the following considerations:

1) Scope of the course: digital signal and image processing, mathematical imaging, computer vision, multimedia.

2) Background of the students: electrical engineering or computer science? How proficient are they with programming?

3) Level of the course: undergraduate or graduate level. Note that there are even attempts to introduce image processing at the high-school level [10].

4) Goals of the interactive tools: demos for complementing the lectures, practical experimentation with images, or/and programming of algorithms.

5) Commercial or freeware: this is an important consideration both from the ethical and economical point of view.

Most teachers want a plug-and-play system that does not have a steep initial learning curve; they also want an immediate visual feed-back of the effect of IP operators [6]. An ideal tool should also be able to solve realistic problems and be relevant for real-world applications [1, 3].

3.1 Commercial packages

Several commercial software packages can be used for setting up image-processing computer laboratories. The most prominent one is Matlab of The MathWork Inc. [11], a high-level programming language that is ideally suited for manipulating vectors and matrices. It is widely used in the scientific community for fast prototyping, and has been adopted by many universities [12] [13]. Matlab with its accompanying Image Processing Toolbox is an attractive framework for teaching image processing [14]. The interactive nature of Matlab also encourages “learning by discovery” [15].

Khoros Pro 2001 of Khoral Inc. [16] is an integrated development environment for image processing with a special module for teaching known as the "Digital Image Processing Course" [17]. Khoros has earned its place as a pedagogical platform for image processing [1] [5] mainly because it offers a visual programming environment coupled with an easy way to link C functions. It also has a large base of users who are willing to exchange their knowledge [18].

Image-processing laboratories have also been developed with other commercial software, including Mathematica [19] of Wolfram Research Inc [20], LabView [21] of National Instruments Corp. [22], or AVS Express [23] of Advanced Visual Systems Inc. [24].

The down side with these commercial products is that they are often expensive, and require the sustained availability of a campus-wide license. In many cases, students are not authorized to use the software at home. For these and other reasons, voices have been raised against the use of commercial software which may conflict with the aims of academic institutions [25]. In addition, many of the packages are platform-dependent and the image-processing operators are often provided as black-box (built-in) routines [23]. Hence, the students do not have access to the core part of the code and cannot visualize intermediate results; this also implies that they cannot easily compare different implementations of an algorithm.

3.2 Non-commercial C-based solutions

Chronologically, the first group of non-commercial offerings is based on the C language (later on also C++) [3] [2]. In [6], the authors argue that the C language is the closest to being universal—it is the choice of many image-processing and numerical-analysis libraries. Some libraries have been developed in academia specifically to provide support for image-processing teaching [26] [27]. The C language gives fast execution code and the students really need to worry about the "hard-core" part of the algorithms. According to [2], students should absolutely know how to handle pointers, which can represent a time-consuming and frustrating task. An interesting class library for image processing (CLIP) [6] was developed to handle memory management tasks—with a small overhead time—and to do other technical and common operations through a small user interface which is easy to learn. Of course, there are also other proposals based on more less common programming languages such as Python [28], Lisp [29] (which uses an unfamiliar syntax and is less adapted to teaching), or Tcl/Tk (the CVIPTools frameworks [30]).

3.3 Non-commercial Java-based solutions

Recently, more and more programmers are turning to Java for writing image processing software that is plateform-independent. Java has also other advantages that are discussed in the next section. Below, we give an overview of available Java packages that can be used for pedagogical purposes, even though not all of them were developed with that specific goal in mind. All these packages are freely available on the Internet.

- NeatVision provides an image-analysis and software development environment [31]. Many of its algorithms are based on a reference book [32]. It has a nice user interface. It is strongly oriented towards computer vision as opposed to signal processing.
- Java Vision Toolkit: (JVT) software library for machine vision and image processing applications [33] [34]. Only few sessions available; the package is rather rudimentary.
- ImageJ: a powerful, full-featured image-processing program developed at the NIH [35]. ImageJ is used on a routine basis by biologists worldwide to assist them with the processing and analysis their images. ImageJ also has an extensive library of plug-ins developed by users.

- Hypertext Image Processing Reference (HIPR): a collection of image-processing resources to illustrate and try-out standard IP operators using interactive applets [36], [37].
- Java Image and Graphics Library (JIGL): image-processing library, but without a graphical user interface [38].
- IPlab with ImageAcess: this is a collection of documented image processing laboratories (downloadable sessions including handouts for the student and software) that was designed by us to take advantage of the features of ImageJ. An important addition is the “ImageAccess” software layer which greatly facilitates the programming of plug-ins, making it accessible to students.

Many of these image-processing frameworks may be used equivalently as a foundation for creating interesting image-processing laboratories. According to us, the availability of a graphical user interface is an important prerequisite to make the software attractive and easy-to-use for the students. In the packages described above, especially the most comprehensive ones, the programming environment offered to the user is often rather general and technical. This is the reason why we developed a “student-friendly” intermediate interface layer, called ImageAccess, to be described in the section "ImageAccess: the interface layer". Even though it was originally designed for ImageJ, it can be ported to other frameworks as well. Presently, in addition to ImageJ, it supports applets for the web, and can cooperate with the Java Virtual Machine integrated into Matlab. It is thus also possible to call Java image-processing routines directly as Matlab functions.

We believe that making the tools and student sessions available to the community through the Internet does not only assist and inspire others to design and share their own classes, but also provides the authors with valuable feedback for further enhancements. We will now give a more detailed description of the system that we are promoting and comment on our experience in using these tools for teaching image processing.

IV. THE IPLAB /IMAGEJ COMBINATION

Our goal in developing IPLab was to offer an environment where the students could implement the algorithms literally as they are seen in the course [39]. It was also an attempt to combine the advantages of low-level languages and high-level languages by borrowing the best from both philosophies.

Specifically, we have chosen to base our system on:

- Java as programming language.
- ImageJ [35], one of the most comprehensive IP freeware available, for a graphical user interface which provides convivial interaction with the full functionality of an image processing application.

- ImageAccess, a “student-friendly” software layer that we have developed to meet the requirements listed in Section 2.2. It simplifies and robustifies the access to pixel data without having to worry about technicalities and the interfacing with ImageJ.
- Sample source code to enable students to extend the algorithm progressively and make them learn by example.

4.1 Java

We have chosen to develop our pedagogical tool in Java. The main arguments in favor of this language are the following: (1) Java is platform-neutral, hence well-adapted to the diversity of the students community; (2) Java is free; (3) Java is network-ready. This makes it possible to develop remote teaching and virtual laboratories [40], even though this is not the way we work—we prefer to maintain contact with our students.

Some authors claim that Java is a natural language for interactive teaching [41], and that it is ready for signal and image processing applications [42]. Java is an object-oriented language which is desirable for image-processing programming [43].

For our part, we add the following arguments:

- Java is robust with a good handling of errors and garbage collection; this eliminates the main source of bugs and crashes;
- Java is syntactically close to C and easy to learn if we provide examples and templates for the methods;
- Java is reasonably fast: applying a 3*3 convolution filter takes only a fraction of a second on a 512*512 pixels image; this means that the students get almost immediate feedback.

Another argument not to be neglected is the “hype” factor: students are attracted by Java, a modern and fashionable language that plays a major role on the Web.

4.2 ImageJ and plug-ins

Our image-processing system is based on a public-domain software: ImageJ. ImageJ is a general-purpose image-processing program; it is the Java offspring of the well-known NIH Image software. As a result, it can run on any platform with a Java Virtual Machine (Mac, Windows, various flavors of Unix, etc…). The application and its source are freely available. The author, Wayne Rasband, is with the National Institutes of Health, Bethesda, Maryland, USA [35].

ImageJ has an open architecture that allows extensibility by addition of Java plug-ins and we take advantage of this functionality for adding our educational plug-ins. Java also provides a mechanism for loading the plug-ins dynamically without having to restart the application after each modification of the code; this functionality offers a fast and comfortable way to edit-compile-execute a program.

Since the programming of ImageJ plug-ins was not originally meant for novice programmers, we have made this process much more transparent and robust for the student. In particular, we provide the function templates and their corresponding commands under the “Plug-ins” menu. They typically take the form of a dialog box, enabling the user to change the parameters of his algorithm. The other key component is our “student-friendly” software layer called ImageAccess (see below), which highly facilitates the programming of image-processing algorithms.

4.3. Sample source code to enable “learning by example”

The students who participate to the image-processing laboratories do not necessarily know Java. Hence, we always provide them with an example of a Java method that does an operation that is similar to the assignment. In particular, we make sure that the example uses the same type of syntax (loops, assignments, mathematical functions) as required for the solution. In addition, we do structure their code by providing empty templates that need to be filled in. This means that a good portion of the assignment can usually be implemented by simple modifications of the example. A sample two-hour session on morphological filtering (handout + software listing) can be viewed at http://bigwww.epfl.ch/teaching/iplabsite/trial.html; the solution can also be run on the Web.

V. IMAGEACCESS: THE INTERFACE LAYER

5.1 Simplified image data access

The key component of our system is the Java class, ImageAccess, that provides a high-level and foolproof interface that lets students safely manipulate images. We have designed it by applying two well-known principles of software development:

- Abstraction. For the user, an image is simply an instance of the ImageAccess class. The pixel data is always retrieved and stored in “double” format, independently of the underlying ImageJ image type. In this way, students do not have to worry about rounding, truncation, or conversion of pixel data. Moreover, pixel data can be accessed “anywhere” through the use of consistent mirror symmetric boundary conditions. For example, when a student wants to retrieve a 3*3 block of an image centered on the upper left corner (0,0), the interface layer provides a full block with “outside” pixel values that are correctly extrapolated. This frees the student from having to worry about what happens at the boundaries and results in more pleasant results (no border artifacts in the output). The aim of applying abstraction is to let the source code express the original algorithm more clearly. The full documentation of the class is available at: http://bigwww.epfl.ch/teaching/iplabsite/Docs/index.html.

- Encapsulation. The fact of working with ImageAccess objects prevents the students from having to worry about implementation details. The typical way to program is to retrieve an image block by using a method that begins with get...(). The block is processed and the result is written in the image using a put...() method. The block can be a single pixel, a row, a column, a 3*3 or a 5*5 neighborhood window.

Conceptually, there is a clear pedagogical advantage in separating as much as possible the image-processing code (algorithm) from the access to the pixels. For our purpose, the latter is a technical part that depends on the language, the platform, or the frame grabber. However, this is not the approach taken in ImageJ because is has a computational cost associated with it. As a result, the typical image-processing routines in ImageJ are faster than ours but also significantly more complicated. Our additional layer leads to an overhead, as illustrated in Table 1 and Table 2. Note that in the case of a separable algorithm where rows and columns are processed in succession, the cost of the access is fixed (e.g. 75 ms), irrespective of the type of processing. For non-separable processing, the access cost is more important: it increases proportionally to the number of pixels in the local neighborhood. We consider the overhead an acceptable price to pay for the substantial simplifications in algorithm transcription. Thanks to this layer, an algorithm can be translated into Java almost literally. This is in contrast with ImageJ's own operators, which need to be implemented for each data type (e.g., byte, 32-bits).

	Computation time
Built-in ImageJ smooth operator (3*3 filtering)	35 ms
Built-in ImageJ convolve operator (3*3 filtering)	200 ms
Our separable implementation of 3*3 filtering with mirror boundary conditions	150 ms
Our non-separable implementation of 3*3 filtering with mirror boundary conditions	325 ms

Table 1.

*Comparison of the computation times for a 3*3 filter: built-in ImageJ routines versus ours (ImageAccess). Experimental conditions: 512*512 pixels image (byte), Java Virtual Machine JRE 1.1.8, Pentium III/500 MHz.*

	Separable implementation		Non-separable implementation	
Kernel size	Algorithm	Access	Algorithm	Access
3*3 averaging	75 ms	75 ms	75 ms	250 ms
5*5 averaging	150 ms	75 ms	175 ms	405 ms
7*7 averaging	200 ms	75 ms	250 ms	640 ms
9*9 averaging	235 ms	75 ms	375 ms	910 ms
11*11 averaging	250 ms	75 ms	500 ms	1280 ms
13*13 averaging	295 ms	75 ms	655 ms	1690 ms

Table 2.

*Cost of the overhead of the access (due to ImageAccess) compared to the cost of the image-processing algorithm itself for the separable and the non-separable implementation of an averaging filter. The access time includes data conversion, the copy of pixel values and implementation of the boundary conditions. Experimental conditions: 512*512 pixels image (byte), Java Virtual Machine JRE 1.1.8, Processor Pentium III/500 MHz.*

5.2 Interfacing with the Web

Programming in Java offers the interesting opportunity to easily port applications to the Web, through the mechanism of applets. In order to easily create stand-alone applets based on the same image-processing source code, our interface layer also comes in an "ImageAccess for Applets" flavor, which can be used exactly the same way by the programmer, but does not make use of ImageJ internally anymore. In this way, we can easily generate and distribute image-processing demonstration applets at a very low development cost. The same image-processing code can therefore be re-used in a plug-in or in an applet (see Fig 1.). Note that such applets are also used to provide on-line examples for the students (some on-line examples can be found at: http://bigwww.epfl.ch/demo/).

5.3. Interfacing with Matlab

Recent versions of Matlab integrate a Java Virtual Machine. Therefore, it becomes possible to run Java image-processing routines directly from the Matlab command window or from a Matlab function. The level of integration is surprisingly high so that Java objects, such as ImageAccess ones, can be handled in a transparent way. The following example (listing 1) illustrates the call of IPlab commands (here, a 2D filter followed by an image display) from Matlab; the data is transferred through the object "im", which contains a copy of the image array used in Matlab.

Listing 1.

JAVA processing and display of an image from Matlab.

```
>> array = 255*rand(100,200);     % creates an array of random variables
>> im = ImageAccess(array);       % copies the array into an ImageAccess object
>> out = Filter.apply(im);        % applies a 2D filtering method
>> out.show('filtered image');    % displays the ImageAccess object
```

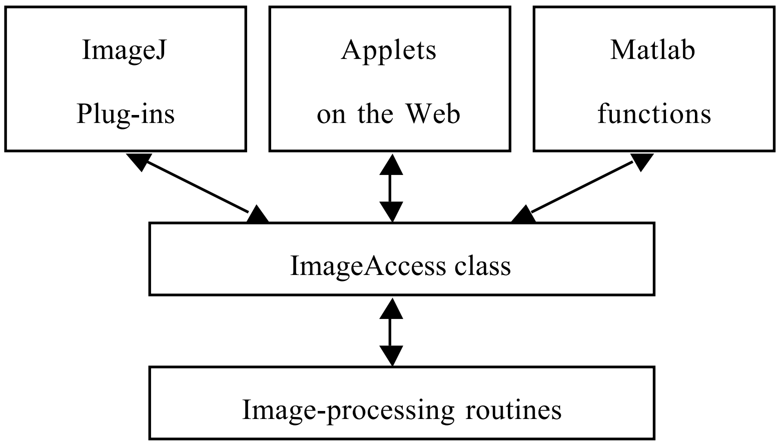


Fig. 1.

The same image-processing routines are used to create a plug-in for ImageJ, to interface with Matlab, or to build a demonstration applet.

VI. EXAMPLES

In this section, we present two examples that illustrate the ease with which image-processing algorithms can be programmed using our interface layer. The code is relatively straightforward; it is essentially a literal translation of the textbook versions of the algorithm.

6.1. Digital filter

We compare two implementations of a digital filter using a non-separable (cf. Listing 2) and a separable algorithm (cf. Listing 3).

Listing 2.

Example of a non-separable filtering template (vertical edge detector) given to the students.

```
public ImageAccess filter2D_NonSeparable(ImageAccess input) {
     int nx = input.getWidth();
     int ny = input.getHeight();
     ImageAccess output = new ImageAccess(nx, ny);
     double block[][] = new double[3][3];
     double value = 0.0;
     for (int x=0; x<nx; x++) {
          for (int y=0; y<ny; y++) {
               input.getNeighborhood(x, y, block);
               value = (block[2][0] - block[0][0] + block[2][1] -
                    block[0][1] + block[2][2] - block[0][2]) / 6.0;
               output.putPixel(x, y, value);
          }
     }
     return output;
}
```

Listing 4.

Example of a separable filtering template (vertical edge detector) given to the students.

```
public ImageAccess filter2D_Separable(ImageAccess input) {
     int nx = input.getWidth();
     int ny = input.getHeight();
     ImageAccess output = new ImageAccess(nx, ny);
     double rowin[]  = new double[nx];
     double rowout[] = new double[nx];
     for (int y=0; y<ny; y++) {
          input.getRow(y, rowin);
          difference3(rowin, rowout);
          output.putRow(y, rowout);
     }
     double colin[]  = new double[ny];
     double colout[] = new double[ny];
     for (int x=0; x<nx; x++) {
          output.getColumn(x, colin);
          average3(colin, colout);
          output.putColumn(x, colout);
     }
     return output;
}

private void average3(double in[], double out[]) {
     int n = in.length;
     out[0] = (2.0 * in[1] + in[0]) / 3.0;
     for (int k=1; k<n-1; k++) {
          out[k] = (in[k-1] + in[k] + in[k+1]) / 3.0;
     }
     out[n-1] = (2.0 * in[n-2] + in[n-1]) / 3.0;
}

private void difference3(double in[], double out[]) {
     int n = in.length;
     out[0] = 0.0;
     for (int k=1; k<n-1; k++) {
          out[k] = (in[k+1] - in[k-1])/2.0;
     }
     out[n-1] = 0.0;
}
```

The separable implementation offers many advantages in terms of computation time and modularity. The code, which is generic for the most of part, clearly shows the two loops, the first one which scans the rows and the second one which scans the columns. The only specific parts are the 1D routines difference3() and average3(), which can be modified easily to yield other separable filters.

In practice, we give these two templates as examples to the students and ask them to program other digital filters such as a horizontal edge detector and a 5*5 moving-average filter (non-separable and separable implementation). By mastering those examples, they get a rather complete exposure to the topic of linear filtering.

6.2. Wavelet transforms

Another interesting example is the implementation of a separable wavelet transform in 2D (c.f. Fig. 2). The students have 3 hours to program the transform and to apply it to various image-processing tasks (simple coding by zeroing out non-significant coefficients, and noise reduction by soft-thresholding). To simplify their task, we give the templates of separable routines for the analysis part; we ask them to code the 1D Haar transform and to write the synthesis part (both 1D and 2D) from scratch.

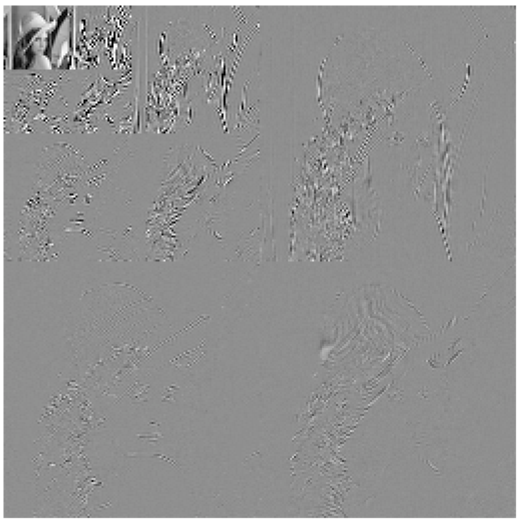


Fig 2.

Haar wavelet transform of Lena (3 iterations across scale)

Listing 3.

Code for the analysis part of the wavelet transform. The high level, data handling routines analysis() and split() are given to the students. Their assignment is to write the code (also shown here) for split_1D() (Haar decomposition) and to implement the 2D inverse transform completely.

```
public ImageAccess analysis(ImageAccess input, int nbScale) {
     int nx = input.getWidth();
     int ny = input.getHeight();
     ImageAccess output = input.duplicate();
     ImageAccess buffer;
     for ( int i=0; i< nbScale; i++) {          // From fine to coarse loop
          buffer = new ImageAccess(nx, ny);     // Create the buffer
          ouput.getSubImage(0, 0, buffer);      // Get the buffer
          buffer = split(buffer);               // Split the buffer
          output.putSubImage(0, 0, buffer);     // Put the buffer
          nx = nx / 2;
          ny = ny / 2;
     }
     return output;
}

private ImageAccess split(ImageAccess input) {
     int nx = input.getWidth();
     int ny = input.getHeight();
     ImageAccess output= new ImageAccess(nx, ny);
     double rowin[]  = new double[nx];
     double rowout[] = new double[nx];
     for (int y=0; y<ny; y++) {
          input.getRow(y, rowin);
          split_1D(rowin, rowout);
          output.putRow(y,rowout);
     }
     double colin[] = new double[ny];
     double colout[] = new double[ny];
     for (int x=0; x<nx; x++) {
          output.getColumn(x, colin);
          split_1D(colin, colout);
          output.putColumn(x,colout);
     }
     return output;
}

private void split_1D(double in[], double out[]) {
     int n = in.length / 2;
     double sqrt2 = Math.sqrt(2.0);
     int k1;
     for (int k=0; k<n; k++) {
          k1 = 2 * k;
          out[k]   = (in[k1] + in[k1+1]) / sqrt2;
          out[k+n] = (in[k1] - in[k1+1]) / sqrt2;
     }
}
```

As far as the students are concerned, this is perhaps one of the most impressive sessions they go through. The great majority of them are capable of completing the full assignment; the 1D routines split_1D and merge_1D for the Haar transform are rather easy—2 liners—and the wavelet synthesis is the same as the analysis, but the other way around.

VII. CLASSROOM

A laboratory session, which is three-hours long, is typically devoted to one chapter of the course. The assignment is given one week in advance. It contains a programming part and an experimental part, where the desired results are processed images. As backup, we usually provide reference versions of the assigned algorithms as executable code (bytecode) to make sure that all students can undertake the experimental part of the assignment under equal conditions; of course, they are greatly encouraged to run their own code and make sure that they get the same results. The sessions take place in 2 computer rooms with 30 Windows 2000 machines in each. There are typically 3 teaching assistants per room for technical assistance. At the end of the session, the students submit their results (source code + processed images) on the Web. The images are checked automatically and the assistants proofread the source code. The students get back their corrected assignments the next week.

The sessions that are currently available are:

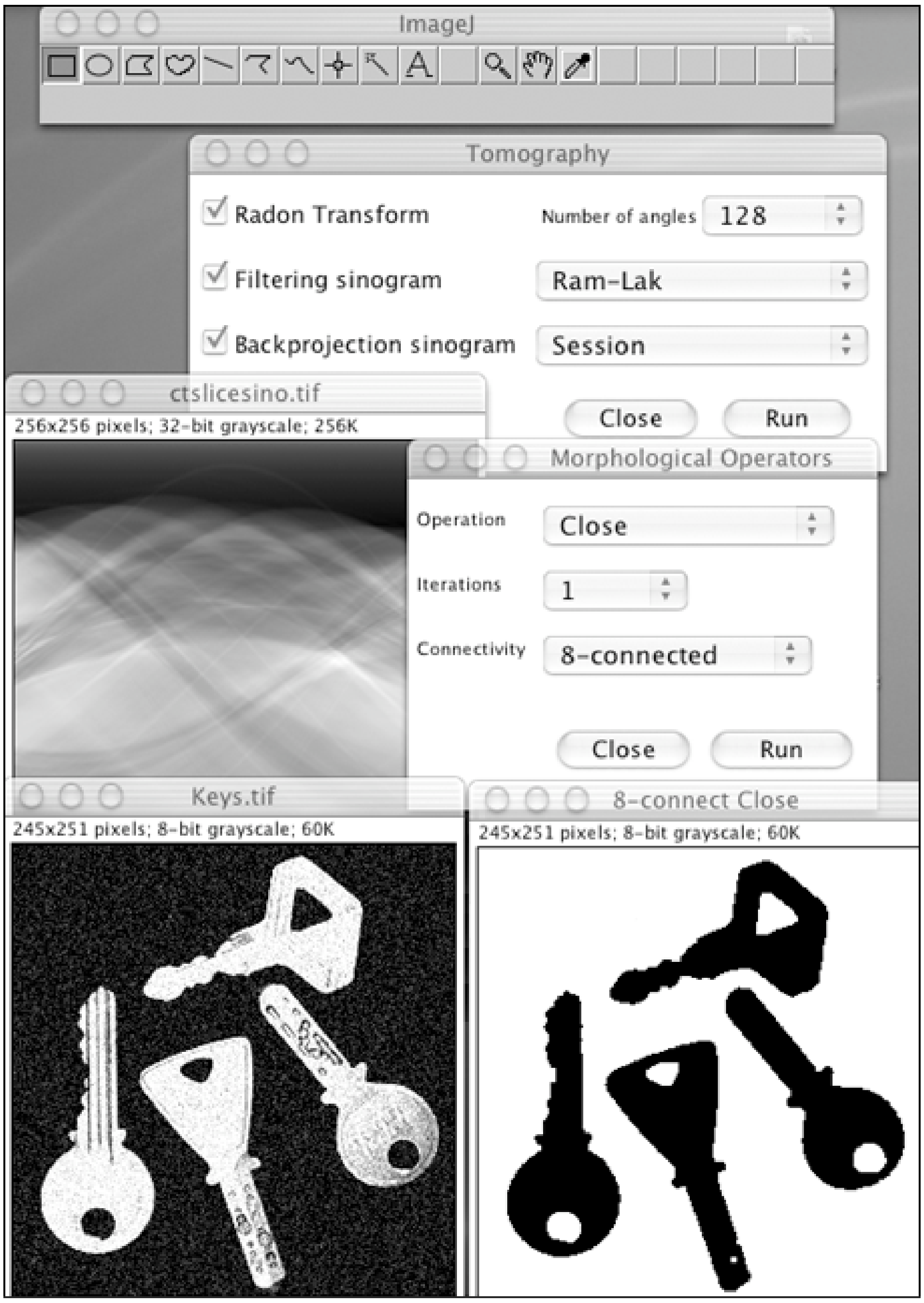
1) Introduction—Understanding of the Fourier transform
2) Digital filtering and applications
3) Morphological operators and applications
4) Edge detection and applications
5) Wavelet transforms
6) Geometric transformation and interpolation
7) Tomography and filtered backprojection
8) Deconvolution (planning)

These session assignments are also available on the web: http://bigwww.epfl.ch/teaching/iplabsite/. Some examples of results with user interfaces are shown in Fig. 3.

Before the introduction of the laboratories, our optional image-processing course normally attracted 15-20 students. With the third edition of the laboratories (term 2002/2003), the number of students went up to 45, which is a good indication of success. The feedback from the students has also been extremely positive.

The combination of “ImageJ” and our interface layer is also used by the students who choose to complete a practical semester or diploma project in our laboratory, which is fully equipped with Macintosh computers. Here, the students develop their new image-processing algorithms using ImageJ and a user-friendly Java integrated development environment (IDE); at the end, they can easily produce a demonstration applet, which is then made available on the Internet.

The students value the fact that the software tools are all freely available on the Web. After downloading ImageJ and a Java development kit (JDK), they are ready to work at home.



Radon Transform ✓ — Number of angles: 128
Filtering sinogram ✓ — Ram-Lak
Backprojection sinogram ✓ — Session

256x256 pixels; 32-bit grayscale; 256K

Operation: Close
Iterations: 1
Connectivity: 8-connected

245x251 pixels; 8-bit grayscale; 60K

245x251 pixels; 8-bit grayscale; 60K

Fig. 3.

Examples of user interface and results for the session 3 and the session 7.

VIII. DISCUSSION AND CONCLUSION

The proposed computer laboratories are a perfect complement to a theoretical course on image processing. Students get active, hands-on practice in image processing which will be valuable to them later in the workplace. They also learn how to implement image-processing algorithms. The computer sessions increase their interest in the course; students like to interact with images and become much more involved as soon as they see some practical relevance. The programming experience raises their curiosity and often stimulates them to do their own experiments. The overall reaction of our students has always been very positive.

As designers of IPLab, we are still astonished by the robustness of Java and ImageJ. The system is quite stable and appears to be robust against the student's programming errors—much more so than any other language or system that we have tested before. Up to now, we have not yet experienced a single crash due to bugs in plug-ins.

The laboratories are entirely based on ImageJ, which is a full featured image-processing software. This package is freely available on the Web, and is still evolving. The students can walk away from the course with an image-processing system that is operational. Using the ImageAccess interface layer, they can easily program both ImageJ plug-ins or Internet applets. The system that we have described may also appeal to practitioners as it offers a simple, full-proof way of developing professional level image processing software.

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