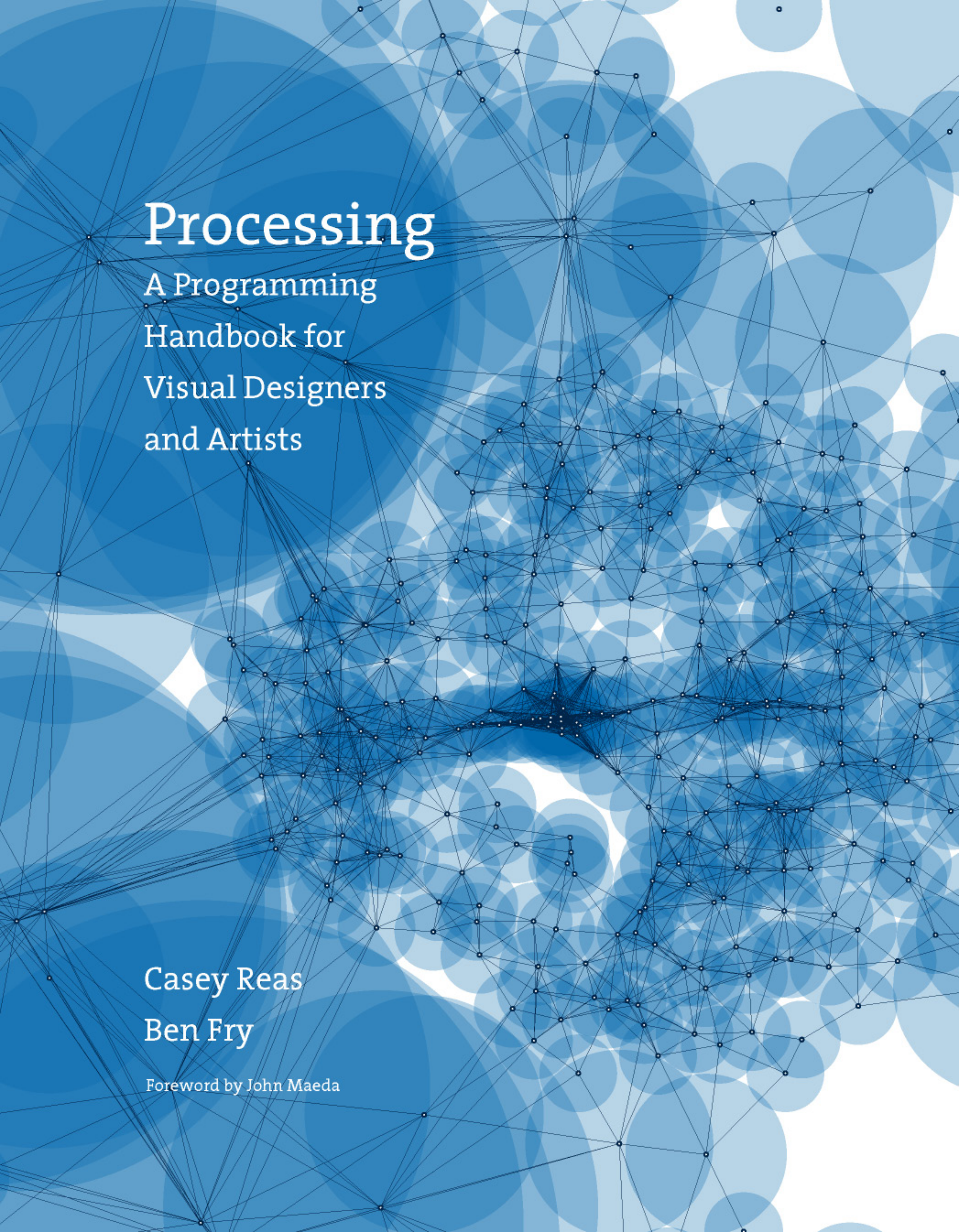

Processing

A Programming Handbook for Visual Designers and Artists

Casey Reas

Ben Fry

Foreword by John Maeda

Processing: a programming handbook for visual designers and artists

Casey Reas
Ben Fry

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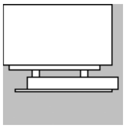
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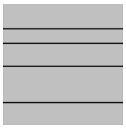
34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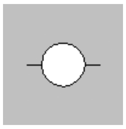
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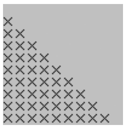
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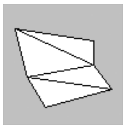
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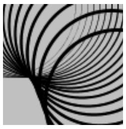
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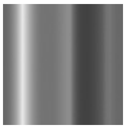
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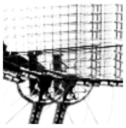
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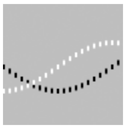
113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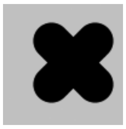
131

141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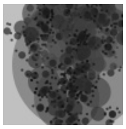
192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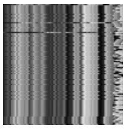
208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225

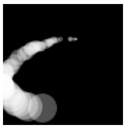
233

244

247

289

297


307

320

324

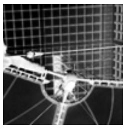
331

336

344

352

354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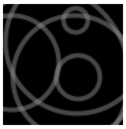
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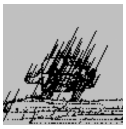
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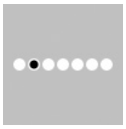
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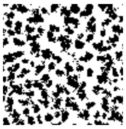
451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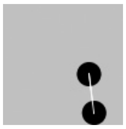
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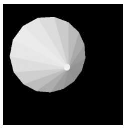
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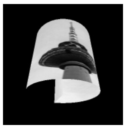
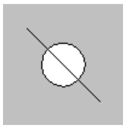

535

551

Contents

88

342

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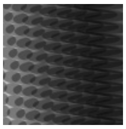
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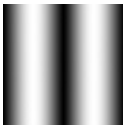
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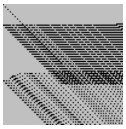
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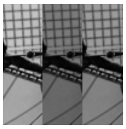
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319

323

351

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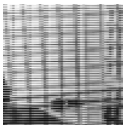
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232

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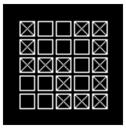
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44

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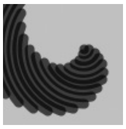
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129

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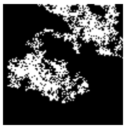
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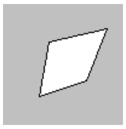
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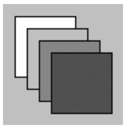
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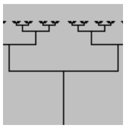
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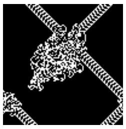
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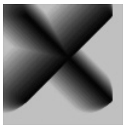
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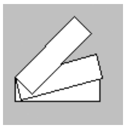
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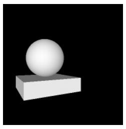
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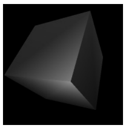
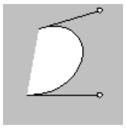

535

551

Contents by category

29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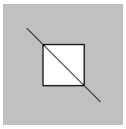
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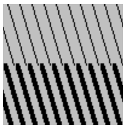
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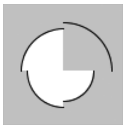
70

83

88

97

113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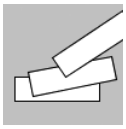
128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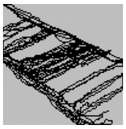
174

186

200

206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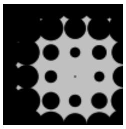
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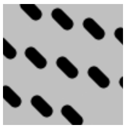
246

281

293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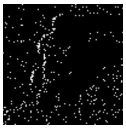
316

322

329

334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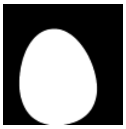
349

353

356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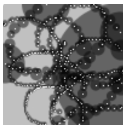
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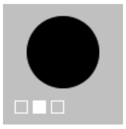
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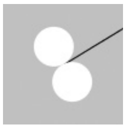
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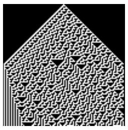
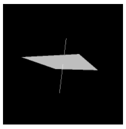

464

484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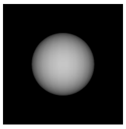
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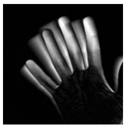

551

Extended contents

Processing...

Processing relates software concepts to principles of visual form, motion, and interaction. It integrates a programming language, development environment, and teaching methodology into a unified system. Processing was created to teach fundamentals of computer programming within a visual context, to serve as a software sketchbook, and to be used as a production tool. Students, artists, design professionals, and researchers use it for learning, prototyping, and production.

The Processing language is a text programming language specifically designed to generate and modify images. Processing strives to achieve a balance between clarity and advanced features. Beginners can write their own programs after only a few minutes of instruction, but more advanced users can employ and write libraries with additional functions. The system facilitates teaching many computer graphics and interaction techniques including vector/raster drawing, image processing, color models, mouse and keyboard events, network communication, and object-oriented programming. Libraries easily extend Processing's ability to generate sound, send/receive data in diverse formats, and to import/export 2D and 3D file formats.

Software

A group of beliefs about the software medium set the conceptual foundation for Processing and inform decisions related to designing the software and environment.

Software is a unique medium with unique qualities
Concepts and emotions that are not possible to express in other media may be expressed in this medium. Software requires its own terminology and discourse and should not be evaluated in relation to prior media such as film, photography, and painting. History shows that technologies such as oil paint, cameras, and film have changed artistic practice and discourse, and while we do not claim that new technologies improve art, we do feel they enable different forms of communication and expression. Software holds a unique position among artistic media because of its ability to produce dynamic forms, process gestures, define behavior, simulate natural systems, and integrate other media including sound, image, and text.

Every programming language is a distinct material
As with any medium, different materials are appropriate for different tasks. When designing a chair, a designer decides to use steel, wood or other materials based on the intended use and on personal ideas and tastes. This scenario transfers to writing software. The abstract animator and programmer Larry Cuba describes his experience this way: "Each of my films has been made on a different system using a different

programming language. A programming language gives you the power to express some ideas, while limiting your abilities to express others."[1] There are many programming languages available from which to choose, and some are more appropriate than others depending on the project goals. The Processing language utilizes a common computer programming syntax that makes it easy for people to extend the knowledge gained through its use to many diverse programming languages.

Sketching is necessary for the development of ideas
It is necessary to sketch in a medium related to the final medium so the sketch can approximate the finished product. Painters may construct elaborate drawings and sketches before executing the final work. Architects traditionally work first in cardboard and wood to better understand their forms in space. Musicians often work with a piano before scoring a more complex composition. To sketch electronic media, it's important to work with electronic materials. Just as each programming language is a distinct material, some are better for sketching than others, and artists working in software need environments for working through their ideas before writing final code. Processing is built to act as a software sketchbook, making it easy to explore and refine many different ideas within a short period of time.

Programming is not just for engineers
Many people think programming is only for people who are good at math and other technical disciplines. One reason programming remains within the domain of this type of personality is that the technically minded people usually create programming languages. It is possible to create different kinds of programming languages and environments that engage people with visual and spatial minds. Alternative languages such as Processing extend the programming space to people who think differently. An early alternative language was Logo, designed in the late 1960s by Seymour Papert as a language concept for children. Logo made it possible for children to program many different media, including a robotic turtle and graphic images on screen. A more contemporary example is the Max programming environment developed by Miller Puckette in the 1980s. Max is different from typical languages; its programs are created by connecting boxes that represent the program code, rather than lines of text. It has generated enthusiasm from thousands of musicians and visual artists who use it as a base for creating audio and visual software. The same way graphical user interfaces opened up computing for millions of people, alternative programming environments will continue to enable new generations of artists and designers to work directly with software. We hope Processing will encourage many artists and designers to tackle software and that it will stimulate interest in other programming environments built for the arts.

Literacy

Processing does not present a radical departure from the current culture of programming. It repositions programming in a way that is accessible to people who are interested in programming but who may be intimidated by or uninterested in the type taught in computer science departments. The computer originated as a tool for fast calculations and has evolved into a medium for expression.

The idea of general software literacy has been discussed since the early 1970s. In 1974, Ted Nelson wrote about the minicomputers of the time in *Computer Lib / Dream Machines*. He explained "the more you know about computers . . . the better your imagination can flow between the technicalities, can slide the parts together, can discern the shapes of what you would have these things do."[2] In his book, Nelson discusses potential futures for the computer as a media tool and clearly outlines ideas for hypertexts (linked text, which set the foundation for the Web) and hypergrams (interactive drawings). Developments at Xerox PARC led to the Dynabook, a prototype for today's personal computers. The Dynabook vision included more than hardware. A programming language was written to enable, for example, children to write storytelling and drawing programs and musicians to write composition programs. In this vision there was no distinction between a computer user and a programmer.

Thirty years after these optimistic ideas, we find ourselves in a different place. A technical and cultural revolution did occur through the introduction of the personal computer and the Internet to a wider audience, but people are overwhelmingly using the software tools created by professional programmers rather than making their own. This situation is described clearly by John Maeda in his book *Creative Code*: "To use a tool on a computer, you need do little more than point and click; to create a tool, you must understand the arcane art of computer programming."[3] The negative aspects of this situation are the constraints imposed by software tools. As a result of being easy to use, these tools obscure some of the computer's potential. To fully explore the computer as an artistic material, it's important to understand this "arcane art of computer programming."

Processing strives to make it possible and advantageous for people within the visual arts to learn how to build their own tools—to become software literate. Alan Kay, a pioneer at Xerox PARC and Apple, explains what literacy means in relation to software:

> The ability to "read" a medium means you can access materials and tools created by others. The ability to "write" in a medium means you can generate materials and tools for others. You must have both to be literate. In print writing, the tools you generate are rhetorical; they demonstrate and convince. In computer writing, the tools you generate are processes; they simulate and decide.[4]

Making processes that simulate and decide requires programming.

Open

The open source software movement is having a major impact on our culture and economy through initiatives such as Linux, but it is having a smaller influence on the culture surrounding software for the arts. There are scattered small projects, but companies such as Adobe and Microsoft dominate software production and therefore control the future of software tools used within the arts. As a group, artists and designers traditionally lack the technical skills to support independent software initiatives. Processing strives to apply the spirit of open source software innovation to the domain of the arts. We want to provide an alternative to available proprietary software and to improve the skills of the arts community, thereby stimulating interest in related initiatives. We want to make Processing easy to extend and adapt and to make it available to as many people as possible.

Processing probably would not exist without its ties to open source software. Using existing open source projects as guidance, and for important software components, has allowed the project to develop in a smaller amount of time and without a large team of programmers. Individuals are more likely to donate their time to an open source project, and therefore the software evolves without a budget. These factors allow the software to be distributed without cost, which enables access to people who cannot afford the high prices of commercial software. The Processing source code allows people to learn from its construction and by extending it with their own code.

People are encouraged to publish the code for programs they've written in Processing. The same way the "view source" function in Web browsers encouraged the rapid proliferation of website-creation skills, access to others' Processing code enables members of the community to learn from each other so that the skills of the community increase as a whole. A good example involves writing software for tracking objects in a video image, thus allowing people to interact directly with the software through their bodies, rather than through a mouse or keyboard. The original submitted code worked well but was limited to tracking only the brightest object in the frame. Karsten Schmidt (a k a toxi), a more experienced programmer, used this code as a foundation for writing more general code that could track multiple colored objects at the same time. Using this improved tracking code as infrastructure enabled Laura Hernandez Andrade, a graduate student at UCLA, to build *Talking Colors*, an interactive installation that superimposes emotive text about the colors people are wearing on top of their projected image. Sharing and improving code allows people to learn from one another and to build projects that would be too complex to accomplish without assistance.

Education

Processing makes it possible to introduce software concepts in the context of the arts and also to open arts concepts to a more technical audience. Because the Processing syntax is derived from widely used programming languages, it's a good base for future learning. Skills learned with Processing enable people to learn other programming languages suitable for different contexts including Web authoring, networking, electronics, and computer graphics.

There are many established curricula for computer science, but by comparison there have been very few classes that strive to integrate media arts knowledge with core concepts of computation. Using classes initiated by John Maeda as a model, hybrid courses based on Processing are being created. Processing has proved useful for short workshops ranging from one day to a few weeks. Because the environment is so minimal, students are able to begin programming after only a few minutes of instruction. The Processing syntax, similar to other common languages, is already familiar to many people, and so students with more experience can begin writing advanced syntax almost immediately.

In a one-week workshop at Hongik University in Seoul during the summer of 2003, the students were a mix of design and computer science majors, and both groups worked toward synthesis. Some of the work produced was more visually sophisticated and some more technically advanced, but it was all evaluated with the same criteria. Students like Soo-jeong Lee entered the workshop without any previous programming experience; while she found the material challenging, she was able to learn the basic principles and apply them to her vision. During critiques, her strong visual skills set an example for the students from more technical backgrounds. Students such as Tai-kyung Kim from the computer science department quickly understood how to use the Processing software, but he was encouraged by the visuals in other students' work to increase his aesthetic sensibility. His work with kinetic typography is a good example of a synthesis between his technical skills and emerging design sensitivity.

Processing is also used to teach longer introductory classes for undergraduates and for topical graduate-level classes. It has been used at small art schools, private colleges, and public universities. At UCLA, for example, it is used to teach a foundation class in digital media to second-year undergraduates and has been introduced to the graduate students as a platform for explorations into more advanced domains. In the undergraduate Introduction to Interactivity class, students read and discuss the topic of interaction and make many examples of interactive systems using the Processing language. Each week new topics such as kinetic art and the role of fantasy in video games are introduced. The students learn new programming skills, and they produce an example of work addressing a topic. For one of their projects, the students read Sherry Turkle's "Video Games and Computer Holding Power"[5] and were given the assignment to write a short game or event exploring their personal desire for escape or transformation. Leon Hong created an elegant flying simulation in which the player floats above a body of water and moves toward a distant island. Muskan Srivastava wrote a game in which the objective was to consume an entire table of desserts within ten seconds.

Teaching basic programming techniques while simultaneously introducing basic theory allows the students to explore their ideas directly and to develop a deep understanding and intuition about interactivity and digital media. In the graduate-level Interactive Environments course at UCLA, Processing is used as a platform for experimentation with computer vision. Using sample code, each student has one week to develop software that uses the body as an input via images from a video camera.

Zai Chang developed a provocative installation called White Noise where participants' bodies are projected as a dense series of colored particles. The shadow of each person is displayed with a different color, and when they overlap, the particles exchange, thus appearing to transfer matter and infect each other with their unique essence. Reading information from a camera is an extremely simple action within the Processing environment, and this facility fosters quick and direct exploration within courses that might otherwise require weeks of programming tutorials to lead up to a similar project.

Network

Processing takes advantage of the strengths of Web-based communities, and this has allowed the project to grow in unexpected ways. Thousands of students, educators, and practitioners across five continents are involved in using the software. The project website serves as the communication hub, but contributors are found remotely in cities around the world. Typical Web applications such as bulletin boards host discussions between people in remote locations about features, bugs, and related events.

Processing programs are easily exported to the Web, which supports networked collaboration and individuals sharing their work. Many talented people have been learning rapidly and publishing their work, thus inspiring others. Websites such as Jared Tarbell's *Complexification.net* and Robert Hodgin's *Flight404.com* present explorations into form, motion, and interaction created in Processing. Tarbell creates images from known algorithms such as Henon Phase diagrams and invents his own algorithms for image creation, such as those from *Substrate*, which are reminiscent of urban patterns (p. 157). On sharing his code from his website, Tarbell writes, "Opening one's code is a beneficial practice for both the programmer and the community. I appreciate modifications and extensions of these algorithms."[6] Hodgin is a self-trained programmer who uses Processing to explore the software medium. It has allowed him to move deeper into the topic of simulating natural forms and motion than he could in other programming environments, while still providing the ability to upload his software to the Internet. His highly trafficked website documents these explorations by displaying the running software as well as providing supplemental text, images, and movies. Websites such as those developed by Jared and Robert are popular destinations for younger artists and designers and other interested individuals. By publishing their work on the Web in this manner they gain recognition within the community.

Many classes taught using Processing publish the complete curriculum on the Web, and students publish their software assignments and source code from which others can learn. The websites for Daniel Shiffman's classes at New York University, for example, include online tutorials and links to the students' work. The tutorials for his Procedural Painting course cover topics including modular programming, image processing, and 3D graphics by combining text with running software examples. Each student maintains a web page containing all of their software and source code created for the class. These pages provide a straightforward way to review performance and make it easy for members of the class to access each others's work.

The Processing website, *www.processing.org*, is a place for people to discuss their projects and share advice. The Processing Discourse section of the website, an online bulletin board, has thousands of members, with a subset actively commenting on each others' work and helping with technical questions. For example, a recent post focused on a problem with code to simulate springs. Over the course of a few days, messages were posted discussing the details of Euler integration in comparison to the Runge-Kutta method. While this may sound like an arcane discussion, the differences between the two methods can be the reason a project works well or fails. This thread and many others like it are becoming concise Internet resources for students interested in detailed topics.

Context

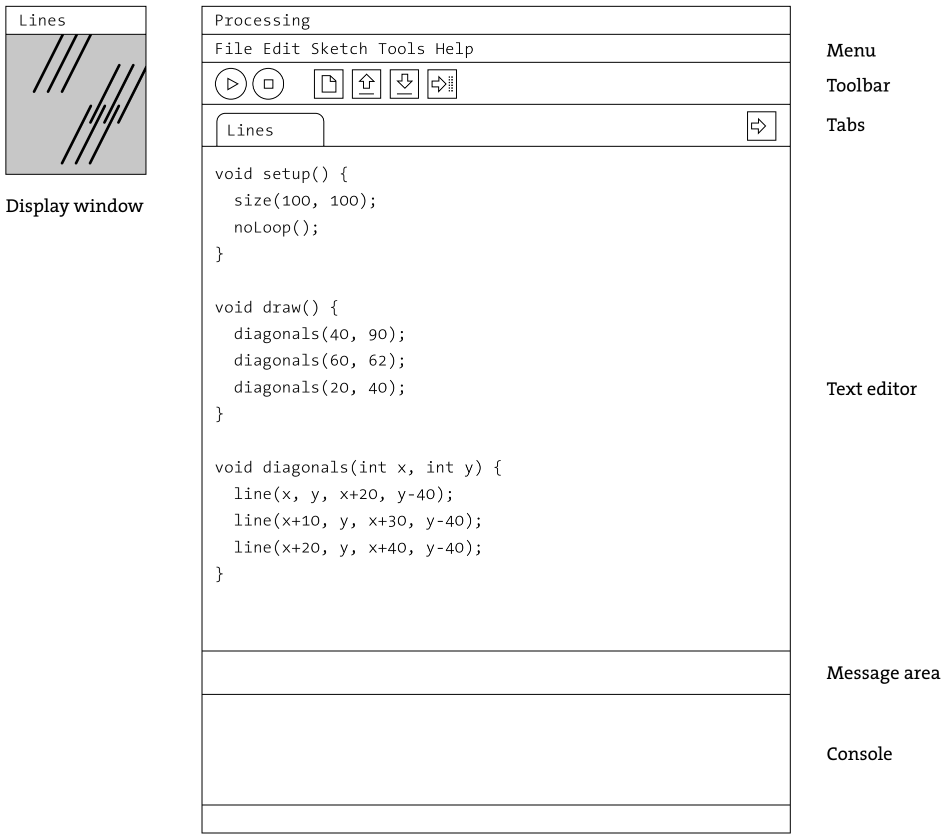
The Processing approach to programming blends with established methods. The core language and additional libraries make use of Java, which also has elements identical to the C programming language. This heritage allows Processing to make use of decades of programming language refinements and makes it understandable to many people who are already familiar with writing software.

Processing is unique in its emphasis and in the tactical decisions it embodies with respect to its context within design and the arts. Processing makes it easy to write software for drawing, animation, and reacting to the environment, and programs are easily extended to integrate with additional media types including audio, video, and electronics. Modified versions of the Processing environment have been built by community members to enable programs to run on mobile phones (p. 617) and to program microcontrollers (p. 633).

The network of people and schools using the software continues to grow. In the five years since the origin on the idea for the software, it has evolved organically through presentations, workshops, classes, and discussions around the globe. We plan to continually improve the software and foster its growth, with the hope that the practice of programming will reveal its potential as the foundation for a more dynamic media.

Notes

1. Larry Cuba, "Calculated Movements," in *Prix Ars Electronica Edition '87: Meisterwerke der Computerkunst* (H. S. Sauer, 1987), p. 111.
2. Theodore Nelson, "Computer Lib / Dream Machines," in *The New Media Reader*, edited by Noah Wardrip-Fruin and Nick Montfort (MIT Press, 2003), p. 306.
3. John Maeda, *Creative Code* (Thames & Hudson, 2004), p. 113.
4. Alan Kay, "User Interface: A Personal View," in *The Art of Human-Computer Interface Design*, edited by Brenda Laurel (Addison-Wesley, 1989), p. 193.
5. Chapter 2 in Sherry Turkle, *The Second Self: Computers and the Human Spirit* (Simon & Schuster, 1984), pp. 64–92.
6. Jared Tarbell, Complexification.net (2004), http://www.complexification.net/medium.html.



```
void setup() {
  size(100, 100);
  noLoop();
}

void draw() {
  diagonals(40, 90);
  diagonals(60, 62);
  diagonals(20, 40);
}

void diagonals(int x, int y) {
  line(x, y, x+20, y-40);
  line(x+10, y, x+30, y-40);
  line(x+20, y, x+40, y-40);
}
```

Processing Development Environment (PDE)
Use the PDE to create programs. Write the code in the text editor and use the buttons in the toolbar to run, save, and export the code.

Using Processing

Download, Install

The Processing software can be downloaded from the Processing website. Using a Web browser, navigate to *www.processing.org/download* and click on the link for your computer's operating system. The Processing software is available for Linux, Macintosh, and Windows. The most up-to-date installation instructions for your operating system are linked from this page.

Environment

The Processing Development Environment (PDE) consists of a simple text editor for writing code, a message area, a text console, tabs for managing files, a toolbar with buttons for common actions, and a series of menus. When programs are run, they open in a new window called the display window.

Pieces of software written using Processing are called sketches. These sketches are written in the text editor. It has features for cutting/pasting and for searching/replacing text. The message area gives feedback while saving and exporting and also displays errors. The console displays text output by Processing programs including complete error messages and text output from programs with the `print()` and `println()` functions. The toolbar buttons allow you to run and stop programs, create a new sketch, open, save, and export.

Run	Compiles the code, opens a display window, and runs the program inside.
Stop	Terminates a running program, but does not close the display window.
New	Creates a new sketch.
Open	Provides a menu with options to open files from the sketchbook, open an example, or open a sketch from anywhere on your computer or network.
Save	Saves the current sketch to its current location. If you want to give the sketch a different name, select "Save As" from the File menu.
Export	Exports the current sketch as a Java applet embedded in an HTML file. The folder containing the files is opened. Click on the *index.html* file to load the software in the computer's default Web browser.

The menus provide the same functionality as the toolbar in addition to actions for file management and opening reference materials.

File	Commands to manage and export files
Edit	Controls for the text editor (Undo, Redo, Cut, Copy, Paste, Find, Replace, etc.)

Sketch	Commands to run and stop programs and to add media files and code libraries.
Tools	Tools to assist in using Processing (automated code formatting, creating fonts, etc.)
Help	Reference files for the environment and language

All Processing projects are called sketches. Each sketch has its own folder. The main program file for each sketch has the same name as the folder and is found inside. For example, if the sketch is named *Sketch_123*, the folder for the sketch will be called *Sketch_123* and the main file will be called *Sketch_123.pde*. The PDE file extension stands for the Processing Development Environment.

A sketch folder sometimes contains other folders for media files and code libraries. When a font or image is added to a sketch by selecting "Add File" from the Sketch menu, a *data* folder is created. You can also add files to your Processing sketch by dragging them into the text editor. Image and sound files dragged into the application window will automatically be added to the current sketch's *data* folder. All images, fonts, sounds, and other data files loaded in the sketch must be in this folder. Sketches are stored in the Processing folder, which will be in different places on your computer or network depending on whether you use PC, Mac, or Linux and on how the preferences are set. To locate this folder, select the "Preferences" option from the File menu (or from the Processing menu on the Mac) and look for the "Sketchbook location."

It is possible to have multiple files in a single sketch. These can be Processing text files (with the extension *.pde*) or Java files (with the extension *.java*). To create a new file, click on the arrow button to the right of the file tabs. This button enables you to create, delete, and rename the files that comprise the current sketch. You can write functions and classes in new PDE files and you can write any Java code in files with the JAVA extension. Working with multiple files makes it easier to reuse code and to separate programs into small subprograms. This is discussed in more detail in Structure 4 (p. 395).

Export

The export feature packages a sketch to run within a Web browser. When code is exported from Processing it is converted into Java code and then compiled as a Java applet. When a project is exported, a series of files are written to a folder named *applet* that is created within the sketch folder. All files from the sketch folder are exported into a single Java Archive (JAR) file with the same name as the sketch. For example, if the sketch is named *Sketch_123*, the exported file will be called *Sketch_123.jar*. The *applet* folder contains the following:

index.html	HTML file with the applet embedded and a link to the source code and the Processing homepage. Double-click this file to open it in the default Web browser.
Sketch_123.jar	Java Archive containing all necessary files for the sketch to run. Includes the Processing core classes, those written for the sketch, and all included media files from the data folder such as images, fonts, and sounds.

Sketch_123.java	The JAVA file generated by the preprocessor from the PDE file. This is the actual file that is compiled into the applet by the Java compiler used in Processing.
Sketch_123.pde	The original program file. It is linked from the index.html file.
loading.gif	An image file displayed while the program is loading in a Web browser.

Every time a sketch is exported, the contents of the *applet* folder are deleted and the files are written from scratch. Any changes previously made to the *index.html* file are lost. Media files not needed for the applet should be deleted from the *data* folder before it is exported to keep the file size small. For example, if there are unused images in the *data* folder, they will be added to the JAR file, thus needlessly increasing its size.

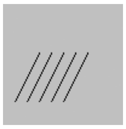
In addition to exporting Java applets for the Web, Processing can also export Java applications for the Linux, Macintosh, and Windows platforms. When "Export Application" is selected from the File menu, folders will be created for each of the operating systems specified in the Preferences. Each folder contains the application, the source code for the sketch, and all required libraries for a specific platform.

Additional and updated information about the Processing environment is available at *www.processing.org/reference/environment* or by selecting the "Environment" item from the Help menu of the Processing application.

Example walk-through

A Processing program can be be as short as one line of code and as long as thousands of lines. This scalability is one of the most important aspects of the language. The following example walk-through presents the modest goal of animating a sequence of diagonal lines as a means to explore some of the basic components of the Processing language. If you are new to programming, some of the terminology and symbols in this section will be unfamiliar. This walk-through is a condensed overview of the entire book, utilizing ideas and techniques that are covered in detail later. Try running these programs inside the Processing application to better understand what the code is doing.

Processing was designed to make it easy to draw graphic elements such as lines, ellipses, and curves in the display window. These shapes are positioned with numbers that define their coordinates. The position of a line is defined by four numbers, two for each endpoint. The parameters used inside the `line()` function determine the position where the line appears. The origin of the coordinate system is in the upper-left corner, and numbers increase right and down. Coordinates and drawing different shapes are discussed on pages 23–30.



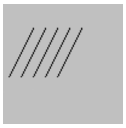
0-01

```
line(10, 80, 30, 40);  // Left line
line(20, 80, 40, 40);
line(30, 80, 50, 40);  // Middle line
line(40, 80, 60, 40);
line(50, 80, 70, 40);  // Right line
```

The visual attributes of shapes are controlled with other code elements that set color and gray values, the width of lines, and the quality of the rendering. Drawing attributes are discussed on pages 31–35.

```
background(0);          // Set the black background                0-02
stroke(255);            // Set line value to white
strokeWeight(5);        // Set line width to 5 pixels
smooth();               // Smooth line edges
line(10, 80, 30, 40);  // Left line
line(20, 80, 40, 40);
line(30, 80, 50, 40);  // Middle line
line(40, 80, 60, 40);
line(50, 80, 70, 40);  // Right line
```

A variable, such as `x`, represents a value; this value replaces the symbol `x` when the code is run. One variable can then control many features of the program. Variables are introduced on page 37-41.

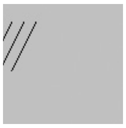
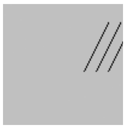


```
int x = 5;   // Set the horizontal position                            0-03
int y = 60;  // Set the vertical position
line(x, y, x+20, y-40);     // Line from [5,60] to [25,20]
line(x+10, y, x+30, y-40); // Line from [15,60] to [35,20]
line(x+20, y, x+40, y-40); // Line from [25,60] to [45,20]
line(x+30, y, x+50, y-40); // Line from [35,60] to [55,20]
line(x+40, y, x+60, y-40); // Line from [45,60] to [65,20]
```

Adding more structure to a program opens further possibilities. The `setup()` and `draw()` functions make it possible for the program to run continuously—this is required to create animation and interactive programs. The code inside `setup()` runs once when the program first starts, and the code inside `draw()` runs continuously. One image frame is drawn to the display window at the end of each loop through `draw()`.

In the following example, the variable `x` is declared as a global variable, meaning it can be assigned and accessed anywhere in the program. The value of `x` increases by 1 each frame, and because the position of the lines is controlled by `x`, they are drawn to a different location each time the value changes. This moves the lines to the right.

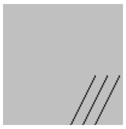
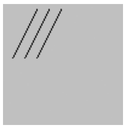
Line 14 in the code is an `if` structure. It contains a relational expression comparing the variable `x` to the value 100. When the expression is `true`, the code inside the block (the code between the { and } associated with the `if` structure) runs. When the relational expression is `false`, the code inside the block does not run. When the value of `x` becomes greater than 100, the line of code inside the block sets the variable `x` to -40, causing the lines to jump to the left edge of the window. The details of `draw()` are discussed on pages 173–175, programming animation is discussed on pages 315–320, and the `if` structure is discussed on pages 53–56.

```
int x = 0;   // Set the horizontal position
int y = 55;  // Set the vertical position

void setup() {
  size(100, 100);  // Set the window to 100 x 100 pixels
}

void draw() {
  background(204);
  line(x, y, x+20, y-40);     // Left line
  line(x+10, y, x+30, y-40);  // Middle line
  line(x+20, y, x+40, y-40);  // Right line
  x = x + 1;      // Add 1 to x
  if (x > 100) {  // If x is greater than 100,
    x = -40;      // assign -40 to x
  }
}
```

0-04

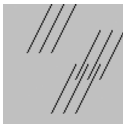
When a program is running continuously, Processing stores data from input devices such as the mouse and keyboard. This data can be used to affect what is happening in the display window. Programs that respond to the mouse are discussed on pages 205–244.

```
void setup() {
  size(100, 100);
}

void draw() {
  background(204);
  // Assign the horizontal value of the cursor to x
  float x = mouseX;
  // Assign the vertical value of the cursor to y
  float y = mouseY;
  line(x, y, x+20, y-40);
  line(x+10, y, x+30, y-40);
  line(x+20, y, x+40, y-40);
}
```

0-05

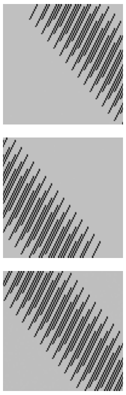
A function is a set of code within a program that performs a specific task. Functions are powerful programming tools that make programs easier to read and change. The `diagonals()` function in the following example was written to draw a sequence of three diagonal lines each time it is run inside `draw()`. Two *parameters*, the numbers in the parentheses after the function name, set the position of the lines. These numbers are passed into the function definition on line 12 and are used as the values for the variables *x* and *y* in lines 13–15. Functions are discussed in more depth on pages 181–196.



0-06

```
void setup() {
  size(100, 100);
  noLoop();
}

void draw() {
  diagonals(40, 90);
  diagonals(60, 62);
  diagonals(20, 40);
}

void diagonals(int x, int y) {
  line(x, y, x+20, y-40);
  line(x+10, y, x+30, y-40);
  line(x+20, y, x+40, y-40);
}
```

The variables used in the previous programs each store one data element. If we want to have 20 groups of lines on screen, it will require 40 variables: 20 for the horizontal positions and 20 for the vertical positions. This can make programming tedious and can make programs difficult to read. Instead of using multiple variable names, we can use *arrays*. An array can store a list of data elements as a single name. A `for` structure can be used to cycle through each array element in sequence. Arrays are discussed on pages 301–313, and the `for` structure is discussed on pages 61–68.



0-07

```
int num = 20;
int[] dx = new int[num];  // Declare and create an array
int[] dy = new int[num];  // Declare and create an array

void setup() {
  size(100, 100);
  for (int i = 0; i < num; i++) {
    dx[i] = i * 5;
    dy[i] = 12 + (i * 6);
  }
}

void draw() {
  background(204);
  for (int i = 0; i < num; i++) {
    dx[i] = dx[i] + 1;
    if (dx[i] > 100) {
      dx[i] = -100;
    }
    diagonals(dx[i], dy[i]);
  }
}

void diagonals(int x, int y) {
  line(x, y, x+20, y-40);
  line(x+10, y, x+30, y-40);
  line(x+20, y, x+40, y-40);
}
```

0-07
cont.

Object-oriented programming is a way of structuring code into *objects*, units of code that contain both data and functions. This style of programming makes a strong connection between groups of data and the functions that act on this data. The `diagonals()` function can be expanded by making it part of a *class* definition. Objects are created using the class as a template. The variables for positioning the lines and setting their drawing attributes then move inside the class definition to be more closely associated with drawing the lines. Object-oriented programming is discussed further on pages 395–411.

0-08

```
Diagonals da, db;

void setup() {
  size(100, 100);
  smooth();
  // Inputs: x, y, speed, thick, gray
  da = new Diagonals(0, 80, 1, 2, 0);
  db = new Diagonals(0, 55, 2, 6, 255);
}

void draw() {
  background(204);
  da.update();
  db.update();
}

class Diagonals {
  int x, y, speed, thick, gray;

  Diagonals(int xpos, int ypos, int s, int t, int g) {
    x = xpos;
    y = ypos;
    speed = s;
    thick = t;
    gray = g;
  }
```

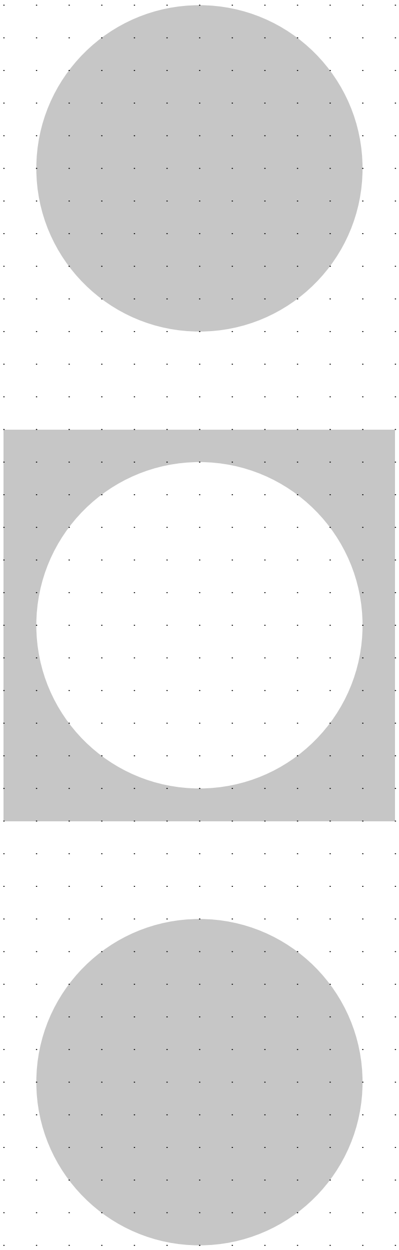
```
    void update() {
      strokeWeight(thick);
      stroke(gray);
      line(x, y, x+20, y-40);
      line(x+10, y, x+30, y-40);
      line(x+20, y, x+40, y-40);
      x = x + speed;
      if (x > 100) {
        x = -100;
      }
    }
  }
```

0-08
cont.

This short walk-through serves to introduce, but not fully explain, some of the core concepts explored in this text. Many key ideas of working with software were mentioned only briefly and others were omitted. Each topic is covered in depth later in the book.

Reference

The reference for the Processing language complements the text in this book. We advise keeping the reference open and consulting it while programming. The reference can be accessed by selecting the "Reference" option from the Help menu within Processing. It's also available online at *www.processing.org/reference*. The reference can also be accessed within the text window. Highlight a word, right-click (or Ctrl-click in Mac OS X), and select "Find in Reference" from the menu that appears. You can also select "Find in Reference" from the Help menu. There are two versions of the Processing reference. The Abridged Reference lists the elements of the Processing language introduced in this book, and the Complete Reference documents additional features.



Shape 1: Coordinates, Primitives

This unit introduces the coordinate system of the display window and a variety of geometric shapes.

Syntax introduced:
```
size(), point(), line(), triangle(), quad(), rect(), ellipse(), bezier()
background(), fill(), stroke(), noFill(), noStroke()
strokeWeight(), strokeCap(), strokeJoin()
smooth(), noSmooth(), ellipseMode(), rectMode()
```

Drawing a shape with code can be difficult because every aspect of its location must be specified with a number. When you're accustomed to drawing with a pencil or moving shapes around on a screen with a mouse, it can take time to start thinking in relation to the screen's strict coordinate grid. The mental gap between seeing a composition on paper or in your mind and translating it into code notation is wide, but easily bridged.

Coordinates

Before making a drawing, it's important to think about the dimensions and qualities of the surface to which you'll be drawing. If you're making a drawing on paper, you can choose from myriad utensils and papers. For quick sketching, newsprint and charcoal are appropriate. For a refined drawing, a smooth handmade paper and range of pencils may be preferred. In contrast, when you are drawing to a computer's screen, the primary options available are the size of the window and the background color.

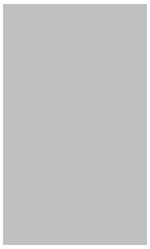
A computer screen is a grid of small light elements called pixels. Screens come in many sizes and resolutions. We have three different types of computer screens in our studios, and they all have a different number of pixels. The laptops have 1,764,000 pixels (1680 wide × 1050 high), the flat panels have 1,310,720 pixels (1280 wide × 1024 high), and the older monitors have 786,432 pixels (1024 wide × 768 high). Millions of pixels may sound like a vast quantity, but they produce a poor visual resolution compared to physical media such as paper. Contemporary screens have a resolution around 100 dots per inch, while many modern printers provide more than 1000 dots per inch. On the other hand, paper images are fixed, but screens have the advantage of being able to change their image many times per second.

Processing programs can control all or a subset of the screen's pixels. When you click the Run button, a display window opens and allows access to reading and writing the pixels within. It's possible to create images larger than the screen, but in most cases you'll make a window the size of the screen or smaller.

The size of the display window is controlled with the `size()` function:

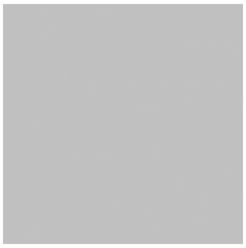
```
size(width, height)
```

The `size()` function has two parameters: the first sets the width of the window and the second sets its height.



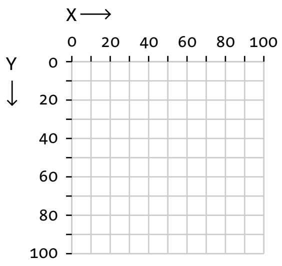
```
// Draw the display window 120 pixels
// wide and 200 pixels high
size(120, 200);
```
2-01

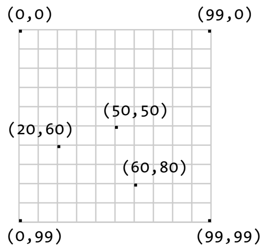
```
// Draw the display window 320 pixels
// wide and 240 pixels high
size(320, 240);
```
2-02



```
// Draw the display window 200 pixels
// wide and 200 pixels high
size(200, 200);
```
2-03

A position on the screen is comprised of an x-coordinate and a y-coordinate. The x-coordinate is the horizontal distance from the origin and the y-coordinate is the vertical distance. In Processing, the origin is the upper-left corner of the display window and coordinate values increase down and to the right. The image on the left shows the coordinate system, and the image on the right shows a few coordinates placed on the grid:





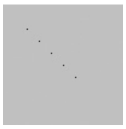
A position is written as the x-coordinate value followed by the y-coordinate, separated with a comma. The notation for the origin is (0,0), the coordinate (50,50) has an x-coordinate of 50 and a y-coordinate of 50, and the coordinate (20,60) is an x-coordinate of 20 and a y-coordinate of 60. If the size of the display window is 100 pixels wide and 100 pixels high, (0,0) is the pixel in the upper-left corner, (99,0) is the pixel in the upper-right corner, (0,99) is the pixel in the lower-left corner, and (99,99) is the pixel in the lower-right corner. This becomes clearer when we look at examples using `point()`.

Primitive shapes

A point is the simplest visual element and is drawn with the `point()` function:

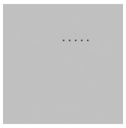
    point(x, y)

This function has two parameters: the first is the x-coordinate and the second is the y-coordinate. Unless specified otherwise, a point is the size of a single pixel.



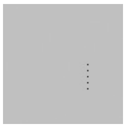
2-04

```
// Points with the same X and Y parameters
// form a diagonal line from the
// upper-left corner to the lower-right corner
point(20, 20);
point(30, 30);
point(40, 40);
point(50, 50);
point(60, 60);
```



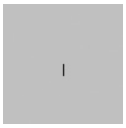
```
// Points with the same Y parameter have the
// same distance from the top and bottom
// edges of the frame
point(50, 30);
point(55, 30);
point(60, 30);
point(65, 30);
point(70, 30);
```

2-05



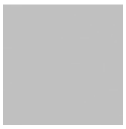
```
// Points with the same X parameter have the
// same distance from the left and right
// edges of the frame
point(70, 50);
point(70, 55);
point(70, 60);
point(70, 65);
point(70, 70);
```

2-06



```
// Placing a group of points next to one
// another creates a line
point(50, 50);
point(50, 51);
point(50, 52);
point(50, 53);
point(50, 54);
point(50, 55);
point(50, 56);
point(50, 57);
point(50, 58);
point(50, 59);
```

2-07



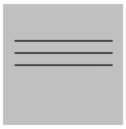
```
// Setting points outside the display
// area will not cause an error,
// but the points won't be visible
point(-500, 100);
point(400, -600);
point(140, 2500);
point(2500, 100);
```

2-08

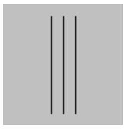
While it's possible to draw any line as a series of points, lines are more simply drawn with the `line()` function. This function has four parameters, two for each endpoint:

```
line(x1, y1, x2, y2)
```

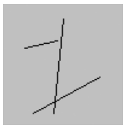
The first two parameters set the position where the line starts and the last two set the position where the line stops.



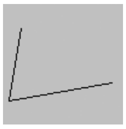
```
// When the y-coordinates for a line are the                  2-09
// same, the line is horizontal
line(10, 30, 90, 30);
line(10, 40, 90, 40);
line(10, 50, 90, 50);
```



```
// When the x-coordinates for a line are the                  2-10
// same, the line is vertical
line(40, 10, 40, 90);
line(50, 10, 50, 90);
line(60, 10, 60, 90);
```



```
// When all four parameters are different,                    2-11
// the lines are diagonal
line(25, 90, 80, 60);
line(50, 12, 42, 90);
line(45, 30, 18, 36);
```

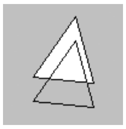


```
// When two lines share the same point they connect           2-12
line(15, 20, 5, 80);
line(90, 65, 5, 80);
```

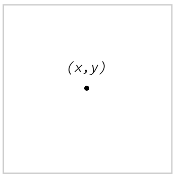
The `triangle()` function draws triangles. It has six parameters, two for each point:

```
triangle(x1, y1, x2, y2, x3, y3)
```

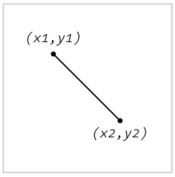
The first pair defines the first point, the middle pair the second point, and the last pair the third point. Any triangle can be drawn by connecting three lines, but the `triangle()` function makes it possible to draw a filled shape. Triangles of all shapes and sizes can be created by changing the parameter values.



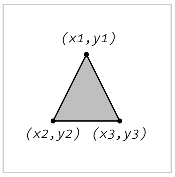
```
triangle(60, 10, 25, 60, 75, 65);  // Filled triangle         2-13
line(60, 30, 25, 80);  // Outlined triangle edge
line(25, 80, 75, 85);  // Outlined triangle edge
line(75, 85, 60, 30);  // Outlined triangle edge
```



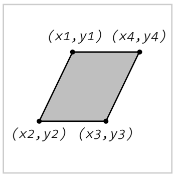
`point(x, y)`



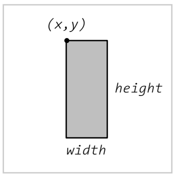
`line(x1, y1, x2, y2)`



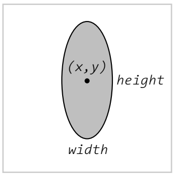
`triangle(x1, y1, x2, y2, x3, y3)`



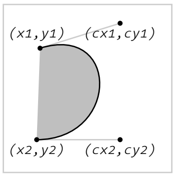
`quad(x1, y1, x2, y2, x3, y3, x4, y4)`



`rect(x, y, width, height)`

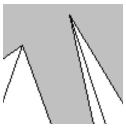


`ellipse(x, y, width, height)`



`bezier(x1, y1, cx1, cy1, cx2, cy2, x2, y2)`

Geometry primitives
Processing has seven functions to assist in making simple shapes. These images show the format for each. Replace the parameters with numbers to use them within a program. These functions are demonstrated in codes 2-04 to 2-22.



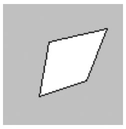
```
triangle(55, 9, 110, 100, 85, 100);
triangle(55, 9, 85, 100, 75, 100);
triangle(-1, 46, 16, 34, -7, 100);
triangle(16, 34, -7, 100, 40, 100);
```

2-14

The `quad()` function draws a quadrilateral, a four-sided polygon. The function has eight parameters, two for each point.

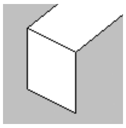
quad(x1, y1, x2, y2, x3, y3, x4, y4)

Changing the parameter values can yield rectangles, squares, parallelograms, and irregular quadrilaterals.



```
quad(38, 31, 86, 20, 69, 63, 30, 76);
```

2-15



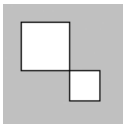
```
quad(20, 20, 20, 70, 60, 90, 60, 40);
quad(20, 20, 70, -20, 110, 0, 60, 40);
```

2-16

Drawing rectangles and ellipses works differently than the shapes previously introduced. Instead of defining each point, the four parameters set the position and the dimensions of the shape. The `rect()` function draws a rectangle:

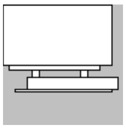
rect(x, y, width, height)

The first two parameters set the location of the upper-left corner, the third sets the width, and the fourth sets the height. Use the same value for the *width* and *height* parameters to draw a square.



```
rect(15, 15, 40, 40);  // Large square
rect(55, 55, 25, 25);  // Small square
```

2-17



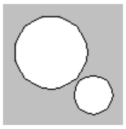
```
rect(0, 0, 90, 50);
rect(5, 50, 75, 4);
rect(24, 54, 6, 6);
rect(64, 54, 6, 6);
rect(20, 60, 75, 10);
rect(10, 70, 80, 2);
```

2-18

The `ellipse()` function draws an ellipse in the display window:

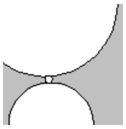
```
ellipse(x, y, width, height)
```

The first two parameters set the location of the center of the ellipse, the third sets the width, and the fourth sets the height. Use the same value for the *width* and *height* parameters to draw a circle.



```
ellipse(40, 40, 60, 60);  // Large circle
ellipse(75, 75, 32, 32);  // Small circle
```

2-19



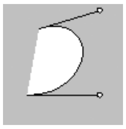
```
ellipse(35, 0, 120, 120);
ellipse(38, 62, 6, 6);
ellipse(40, 100, 70, 70);
```

2-20

The `bezier()` function can draw lines that are not straight. A Bézier curve is defined by a series of control points and anchor points. A curve is drawn between the anchor points, and the control points define its shape:

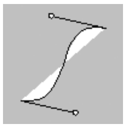
```
bezier(x1, y1, cx1, cy1, cx2, cy2, x2, y2)
```

The function requires eight parameters to set four points. The curve is drawn between the first and fourth points, and the control points are defined by the second and third points. In software that uses Bézier curves, such as Adobe Illustrator, the control points are represented by the tiny handles that protrude from the edge of a curve.



```
bezier(32, 20, 80, 5, 80, 75, 30, 75);
// Draw the control points
line(32, 20, 80, 5);
ellipse(80, 5, 4, 4);
line(80, 75, 30, 75);
ellipse(80, 75, 4, 4);
```

2-21

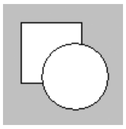


```
bezier(85, 20, 40, 10, 60, 90, 15, 80);
// Draw the control points
line(85, 20, 40, 10);
ellipse(40, 10, 4, 4);
line(60, 90, 15, 80);
ellipse(60, 90, 4, 4);
```

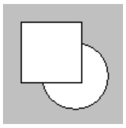
2-22

Drawing order

The order in which shapes are drawn in the code defines which shapes appear on top of others in the display window. If a rectangle is drawn in the first line of a program, it is drawn behind an ellipse drawn in the second line of the program. Reversing the order places the rectangle on top.



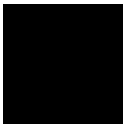
```
rect(15, 15, 50, 50);     // Bottom
ellipse(60, 60, 55, 55);  // Top
```
2-23



```
ellipse(60, 60, 55, 55);  // Bottom
rect(15, 15, 50, 50);     // Top
```
2-24

Gray values

The examples so far have used the default light-gray background, black lines, and white shapes. To change these default values, it's necessary to introduce additional syntax. The `background()` function sets the color of the display window with a number between 0 and 255. This range may be awkward if you're not familiar with drawing software on the computer. The value 255 is white and the value 0 is black, with a range of gray values in between. If no background value is defined, the default value 204 (light gray) is used.

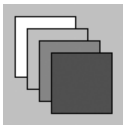


```
background(0);
```
2-25

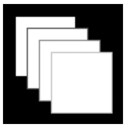
```
background(124);
```
2-26

```
background(230);
```
2-27

The fill() function sets the fill value of shapes, and the stroke() function sets the outline value of the drawn shapes. If no fill value is defined, the default value of 255 (white) is used. If no stroke value is defined, the default value of 0 (black) is used.

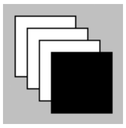


```
rect(10, 10, 50, 50);                                2-28
fill(204);  // Light gray
rect(20, 20, 50, 50);
fill(153);  // Middle gray
rect(30, 30, 50, 50);
fill(102);  // Dark gray
rect(40, 40, 50, 50);
```



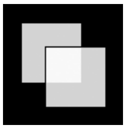
```
background(0);                                       2-29
rect(10, 10, 50, 50);
stroke(102); // Dark gray
rect(20, 20, 50, 50);
stroke(153); // Middle gray
rect(30, 30, 50, 50);
stroke(204); // Light gray
rect(40, 40, 50, 50);
```

Once a fill or stroke value is defined, it applies to all shapes drawn afterward. To change the fill or stroke value, use the fill() or stroke() function again.

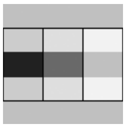


```
fill(255);  // White                                 2-30
rect(10, 10, 50, 50);
rect(20, 20, 50, 50);
rect(30, 30, 50, 50);
fill(0);  // Black
rect(40, 40, 50, 50);
```

An optional second parameter to fill() and stroke() controls transparency. Setting the parameter to 255 makes the shape entirely opaque, and 0 is totally transparent:



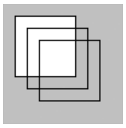
```
background(0);                                       2-31
fill(255, 220);
rect(15, 15, 50, 50);
rect(35, 35, 50, 50);
```



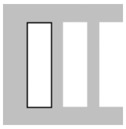
```
fill(0);                                             2-32
rect(0, 40, 100, 20);
fill(255, 51);   // Low opacity
rect(0, 20, 33, 60);
fill(255, 127);  // Medium opacity
```

```
rect(33, 20, 33, 60);
fill(255, 204);  // High opacity
rect(66, 20, 33, 60);
```
2-32 cont.

The stroke and fill of a shape can be disabled. The `noFill()` function stops Processing from filling shapes, and the `noStroke()` function stops lines from being drawn and shapes from having outlines. If `noFill()` and `noStroke()` are both used, nothing will be drawn to the screen.



```
rect(10, 10, 50, 50);
noFill();  // Disable the fill
rect(20, 20, 50, 50);
rect(30, 30, 50, 50);
```
2-33

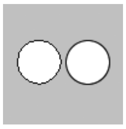


```
rect(20, 15, 20, 70);
noStroke();  // Disable the stroke
rect(50, 15, 20, 70);
rect(80, 15, 20, 70);
```
2-34

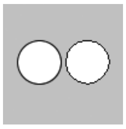
Setting color fill and stroke values is introduced in Color 1 (p. 85).

Drawing attributes

In addition to changing the fill and stroke values of shapes, it's also possible to change attributes of the geometry. The `smooth()` and `noSmooth()` functions enable and disable smoothing (also called antialiasing). Once these functions are used, all shapes drawn afterward are affected. If `smooth()` is used first, using `noSmooth()` cancels the setting, and vice versa.



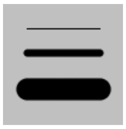
```
ellipse(30, 48, 36, 36);
smooth();
ellipse(70, 48, 36, 36);
```
2-35



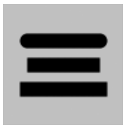
```
smooth();
ellipse(30, 48, 36, 36);
noSmooth();
ellipse(70, 48, 36, 36);
```
2-36

Line attributes are controlled by the `strokeWeight()`, `strokeCap()`, and `strokeJoin()` functions. The `strokeWeight()` function has one numeric parameter that sets the thickness of all lines drawn after the function is used. The `strokeCap()` function requires one parameter that can be either `ROUND`, `SQUARE`, or `PROJECT`.

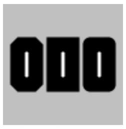
ROUND makes round endpoints, and SQUARE squares them. PROJECT is a mix of the two that extends a SQUARE endpoint by the radius of the line. The strokeJoin() function has one parameter that can be either BEVEL, MITER, or ROUND. These parameters determine the way line segments or the stroke around a shape connects. BEVEL causes lines to join with squared corners, MITER is the default and joins lines with pointed corners, and ROUND creates a curve.



```
smooth();                                                     2-37
line(20, 20, 80, 20);  // Default line weight of 1
strokeWeight(6);
line(20, 40, 80, 40);  // Thicker line
strokeWeight(18);
line(20, 70, 80, 70);  // Beastly line
```



```
smooth();                                                     2-38
strokeWeight(12);
strokeCap(ROUND);
line(20, 30, 80, 30);  // Top line
strokeCap(SQUARE);
line(20, 50, 80, 50);  // Middle line
strokeCap(PROJECT);
line(20, 70, 80, 70);  // Bottom line
```

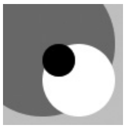


```
smooth();                                                     2-39
strokeWeight(12);
strokeJoin(BEVEL);
rect(12, 33, 15, 33);  // Left shape
strokeJoin(MITER);
rect(42, 33, 15, 33);  // Middle shape
strokeJoin(ROUND);
rect(72, 33, 15, 33);  // Right shape
```

Shape 2 (p. 69) and Shape 3 (p. 197) show how to draw shapes with more flexibility.

Drawing modes

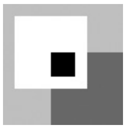
By default, the parameters for ellipse() set the x-coordinate of the center, the y-coordinate of the center, the width, and the height. The ellipseMode() function changes the way these parameters are used to draw ellipses. The ellipseMode() function requires one parameter that can be either CENTER, RADIUS, CORNER, or CORNERS. The default mode is CENTER. The RADIUS mode also uses the first and second parameters of ellipse() to set the center, but causes the third parameter to set half of the width and the fourth parameter to set half of the height. The CORNER mode makes ellipse() work similarly to rect(). It causes the first and second parameters to position the upper-left corner of the rectangle that circumscribes the ellipse and uses the third and fourth parameters to set the width and height. The CORNERS mode has a similar affect to CORNER, but is causes the third and fourth parameters to ellipse() to set the lower-right corner of the rectangle.



2-40

```
smooth();
noStroke();
ellipseMode(RADIUS);
fill(126);
ellipse(33, 33, 60, 60);  // Gray ellipse
fill(255);
ellipseMode(CORNER);
ellipse(33, 33, 60, 60);  // White ellipse
fill(0);
ellipseMode(CORNERS);
ellipse(33, 33, 60, 60);  // Black ellipse
```

In a similar fashion, the rectMode() function affects how rectangles are drawn. It requires one parameter that can be either CORNER, CORNERS, or CENTER. The default mode is CORNER, and CORNERS causes the third and fourth parameters of rect() to draw the corner opposite the first. The CENTER mode causes the first and second parameters of rect() to set the center of the rectangle and uses the third and fourth parameters as the width and height.



2-41

```
noStroke();
rectMode(CORNER);
fill(126);
rect(40, 40, 60, 60);     // Gray ellipse
rectMode(CENTER);
fill(255);
rect(40, 40, 60, 60);     // White ellipse
rectMode(CORNERS);
fill(0);
rect(40, 40, 60, 60);     // Black ellipse
```

Exercises

1. *Create a composition by carefully positioning one line and one ellipse.*
2. *Modify the code for exercise 1 to change the fill, stroke, and background values.*
3. *Create a visual knot using only Bézier curves.*

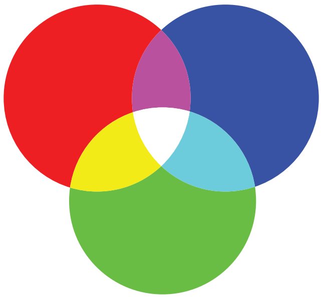
Color 1: Color by Numbers

This unit introduces code elements and concepts for working with color in software.

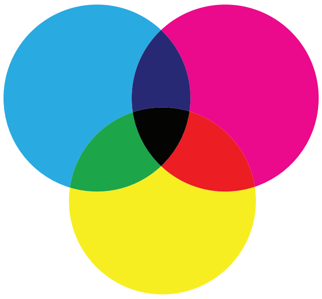
Syntax introduced:
`color, color(), colorMode()`

When Casey and Ben studied color in school, they spent hours carefully mixing paints and applying it to sheets of paper. They cut paper into perfect squares and carefully arranged them into precise gradations from blue to orange, white to yellow, and many other combinations. Over time, they developed an intuition that allowed them to achieve a specific color value by mixing the appropriate components. Through focused labor, they learned how to isolate properties of color, understand the interactions between colors, and discuss qualities of color.

Working with color on screen is different from working with color on paper or canvas. While the same rigor applies, knowledge of pigments for painting (cadmium red, Prussian blue, burnt umber) and from printing (cyan, yellow, magenta) does not translate into the information needed to create colors for digital displays. For example, adding all the colors together on a computer monitor produces white, while adding all the colors together with paint produces black (or a strange brown). A computer monitor mixes colors with light. The screen is a black surface, and colored light is added. This is known as additive color, in contrast to the subtractive color model for inks on paper and canvas. This image presents the difference between these models:



Additive color



Subtractive color

The most common way to specify color on the computer is with RGB values. An RGB value sets the amount of red, green, and blue light in a single pixel of the screen. If you look closely at a computer monitor or television screen, you will see that each pixel is comprised of three separate light elements of the colors red, green, and blue; but because our eyes can see only a limited amount of detail, the three colors mix to create a single color. The intensities of each color element are usually specified with values between 0 and 255 where 0 is the minimum and 255 is the maximum. Many software applications also use this range. Setting the red, green, and blue components to 0 creates black. Setting these components to 255 creates white. Setting red to 255 and green and blue to 0 creates an intense red.

Selecting colors with convenient numbers can save effort. For example, it's common to see the parameters (0, 0, 255) used for blue and (0, 255, 0) for green. These combinations are often responsible for the garish coloring associated with technical images produced on the computer. They seem extreme and unnatural because they don't account for the human eye's ability to distinguish subtle values. Colors that appeal to our eyes are usually not convenient numbers. Rather than picking numbers like 0 and 255, try using a color selector and choosing colors. Processing's color selector is opened from the Tools menu. Colors are selected by clicking a location on the color field or by entering numbers directly. For example, in the figure on the facing page, the current blue selected is defined by an R value of 35, a G value of 211, and a B value of 229. These numbers can be used to recreate the chosen color in your code.

Setting colors

In Processing, colors are defined by the parameters to the `background()`, `fill()`, and `stroke()` functions:

```
background(value1, value2, value3)
fill(value1, value2, value3)
fill(value1, value2, value3, alpha)
stroke(value1, value2, value3)
stroke(value1, value2, value3, alpha)
```

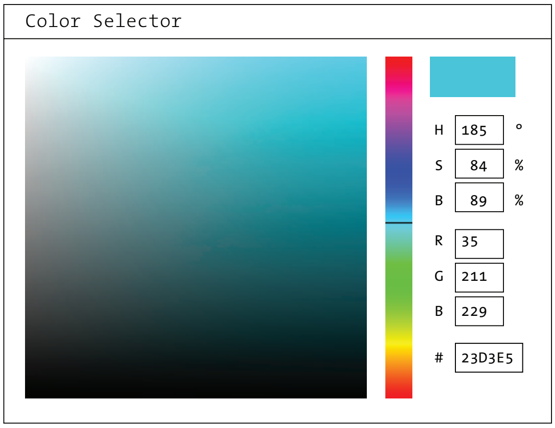
By default, the *value1* parameter defines the red color component, *value2* the green component, and *value3* the blue. The optional alpha parameter to `fill()` or `stroke()` defines the transparency. The *alpha* parameter value 255 means the color is entirely opaque, and the value 0 means it's entirely transparent (it won't be visible).

```
background(242, 204, 47);
```

9-01

```
background(174, 221, 60);
```

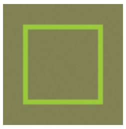
9-02



Color Selector
Drag the cursor inside the window or input numbers to select a color. The large square area determines the saturation and brightness, and the thin vertical strip determines the hue. The numeric value of the selected color is displayed in HSB, RGB, and hexadecimal notation.

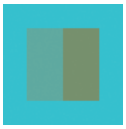
```
background(129, 130, 87);
noStroke();
fill(174, 221, 60);
rect(17, 17, 66, 66);
```

9-03



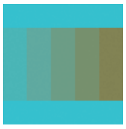
```
background(129, 130, 87);
noFill();
strokeWeight(4);
stroke(174, 221, 60);
rect(19, 19, 62, 62);
```

9-04



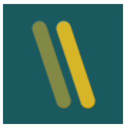
```
background(116, 193, 206);
noStroke();
fill(129, 130, 87, 102);  // More transparent
rect(20, 20, 30, 60);
fill(129, 130, 87, 204);  // Less transparent
rect(50, 20, 30, 60);
```

9-05



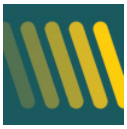
```
background(116, 193, 206);
int x = 0;
noStroke();
for (int i = 51; i <= 255; i += 51) {
  fill(129, 130, 87, i);
  rect(x, 20, 20, 60);
  x += 20;
}
```

9-06



```
background(56, 90, 94);
smooth();
strokeWeight(12);
stroke(242, 204, 47, 102);  // More transparency
line(30, 20, 50, 80);
stroke(242, 204, 47, 204);  // Less transparency
line(50, 20, 70, 80);
```

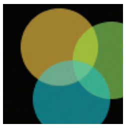
9-07



```
background(56, 90, 94);
smooth();
int x = 0;
strokeWeight(12);
for (int i = 51; i <= 255; i += 51) {
  stroke(242, 204, 47, i);
  line(x, 20, x+20, 80);
  x += 20;
}
```

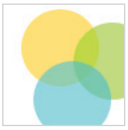
9-08

Transparency can be used to create new colors by overlapping shapes. The colors originating from overlaps depend on the order in which the shapes are drawn.



```
background(0);
noStroke();
smooth();
fill(242, 204, 47, 160);   // Yellow
ellipse(47, 36, 64, 64);
fill(174, 221, 60, 160);   // Green
ellipse(90, 47, 64, 64);
fill(116, 193, 206, 160);  // Blue
ellipse(57, 79, 64, 64);
```

9-09



```
background(255);
noStroke();
smooth();
fill(242, 204, 47, 160);   // Yellow
ellipse(47, 36, 64, 64);
fill(174, 221, 60, 160);   // Green
ellipse(90, 47, 64, 64);
fill(116, 193, 206, 160);  // Blue
ellipse(57, 79, 64, 64);
```

9-10

Color data

The `color` data type is used to store colors in a program, and the `color()` function is used to assign a `color` variable. The `color()` function can create gray values, gray values with transparency, color values, and color values with transparency. Variables of the `color` data type can store all of these configurations:

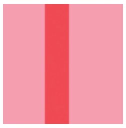
```
color(gray)
color(gray, alpha)
color(value1, value2, value3)
color(value1, value2, value3, alpha)
```

The parameters of the `color()` function define a color. The *`gray`* parameter used alone or with *`alpha`* defines tones ranging from white to black. The *`alpha`* parameter defines transparency with values ranging from 0 (transparent) to 255 (opaque). The *`value1`*, *`value2`*, and *`value3`* parameters define values for the different components. Variables of the `color` data type are defined and assigned in the same way as the `int` and `float` data types discussed in Data 1 (p. 37).

9-11

```
color c1 = color(51);                // Creates gray
color c2 = color(51, 204);           // Creates gray with transparency
color c3 = color(51, 102, 153);      // Creates blue
color c4 = color(51, 102, 153, 51);  // Creates blue with transparency
```

After a `color` variable has been defined, it can be used as the parameter to the `background()`, `fill()`, and `stroke()` functions.

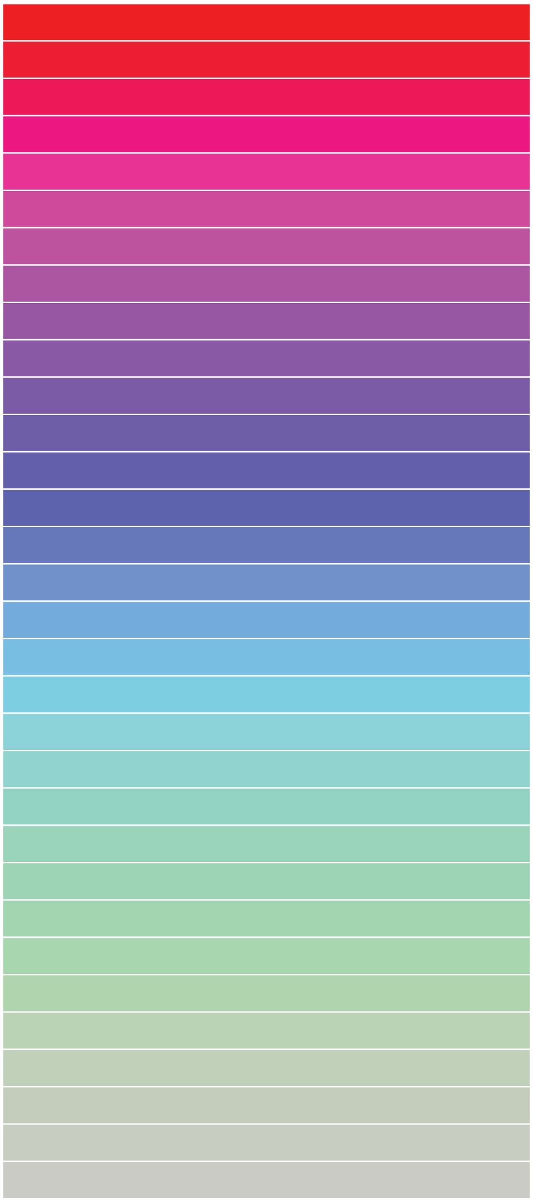


9-12

```
color ruby = color(211, 24, 24, 160);
color pink = color(237, 159, 176);
background(pink);
noStroke();
fill(ruby);
rect(35, 0, 20, 100);
```

RGB, HSB

Processing uses the RGB color model as its default for working with color, but the HSB specification can be used instead to define colors in terms of their hue, saturation, and brightness. The hue of a color is what most people normally think of as the color name: yellow, red, blue, orange, green, violet. A pure hue is an undiluted color at its most intense. The saturation is the degree of purity in a color. It is the continuum from the undiluted, pure hue to its most diluted and dull. The brightness of a color is its relation to light and dark.



RGB			HSB			HEX
255	0	0	360	100	100	#FF0000
252	9	45	351	96	99	#FC0A2E
249	16	85	342	93	98	#F91157
249	23	126	332	90	98	#F91881
246	31	160	323	87	97	#F720A4
244	38	192	314	84	96	#F427C4
244	45	226	304	81	96	#F42EE7
226	51	237	295	78	95	#E235F2
196	58	237	285	75	95	#C43CF2
171	67	234	276	71	94	#AB45EF
148	73	232	267	68	93	#944BED
126	81	232	257	65	93	#7E53ED
108	87	229	248	62	92	#6C59EA
95	95	227	239	59	91	#5F61E8
102	122	227	229	56	91	#667DE8
107	145	224	220	53	90	#6B94E5
114	168	224	210	50	90	#72ACE5
122	186	221	201	46	89	#7ABEE2
127	200	219	192	43	88	#7FCDE0
134	216	219	182	40	88	#86DDE0
139	216	207	173	37	87	#8BDDD4
144	214	195	164	34	86	#90DBC7
151	214	185	154	31	86	#97DBBD
156	211	177	145	28	85	#9CD8B5
162	211	172	135	25	85	#A2D8B0
169	209	169	126	21	84	#A9D6AD
175	206	169	117	18	83	#AFD3AD
185	206	175	107	15	83	#BAD3B3
192	204	180	98	12	82	#C1D1B8
197	201	183	89	9	81	#C5CEBB
202	201	190	79	6	81	#CACEC2
202	200	193	70	3	80	#CACCC5

Color by numbers
Every color within a program is set by numbers, and there are more than 16 million colors to choose from. This diagram presents a few colors and their corresponding numbers for the RGB and HSB color models. The RGB column is in relation to `colorMode(RGB, 255)` *and the HSB column is in relation to* `colorMode(HSB, 360, 100, 100)`.

The `colorMode()` function sets the color space for a program:

```
colorMode(mode)
colorMode(mode, range)
colorMode(mode, range1, range2, range3)
```

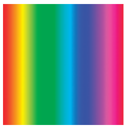
The parameters to `colorMode()` change the way Processing interprets color data. The *mode* parameter can be either RGB or HSB. The range parameters allow Processing to use different values than the default of 0 to 255. A range of values frequently used in computer graphics is between 0.0 and 1.0. Either a single range parameter sets the range for all the color components, or the *range1*, *range2*, and *range3* parameters set the range for each—either red, green, blue or hue, saturation, brightness, depending on the value of the *mode* parameter.

9-13
```
// Set the range for the red, green, and blue values from 0.0 to 1.0
colorMode(RGB, 1.0);
```

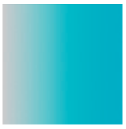
A useful setting for HSB mode is to set the *range1*, *range2*, and *range3* parameters respectively to 360, 100, and 100. The hue values from 0 to 360 are the degrees around the color wheel, and the saturation and brightness values from 0 to 100 are percentages. This setting matches the values used in many color selectors and therefore makes it easy to transfer color data between other programs and Processing:

9-14
```
// Set the range for the hue to values from 0 to 360 and the
// saturation and brightness to values between 0 and 100
colorMode(HSB, 360, 100, 100);
```

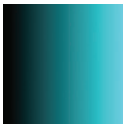
The following examples reveal the differences between hue, saturation, and brightness.



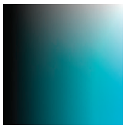
9-15
```
// Change the hue, saturation and brightness constant
colorMode(HSB);
for (int i = 0; i < 100; i++) {
  stroke(i*2.5, 255, 255);
  line(i, 0, i, 100);
}
```



9-16
```
// Change the saturation, hue and brightness constant
colorMode(HSB);
for (int i = 0; i < 100; i++) {
  stroke(132, i*2.5, 204);
  line(i, 0, i, 100);
}
```

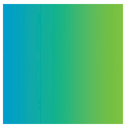


```
// Change the brightness, hue and saturation constant          9-17
colorMode(HSB);
for (int i = 0; i < 100; i++) {
  stroke(132, 108, i*2.5);
  line(i, 0, i, 100);
}
```

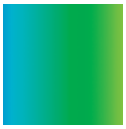


```
// Change the saturation and brightness, hue constant          9-18
colorMode(HSB);
for (int i = 0; i < 100; i++) {
  for (int j = 0; j < 100; j++) {
    stroke(132, j*2.5, i*2.5);
    point(i, j);
  }
}
```

It's easy to make smooth transitions between colors by changing the values used for `color()`, `fill()`, and `stroke()`. The HSB model has an enormous advantages over the RGB model when working with code because it's more intuitive. Changing the values of the red, green, and blue components often has unexpected results, while estimating the results of changes to hue, saturation, and brightness follows a more logical path. The following examples show a transition from green to blue. The first example makes this transition using the RGB model. It requires calculating all three color values, and the saturation of the color unexpectedly changes in the middle. The second example makes the transition using the HSB model. Only one number needs to be altered, and the hue changes smoothly and independently from the other color properties.



```
// Shift from blue to green in RGB mode                        9-19
colorMode(RGB);
for (int i = 0; i < 100; i++) {
  float r = 61 + (i*0.92);
  float g = 156 + (i*0.48);
  float b = 204 - (i*1.43);
  stroke(r, g, b);
  line(i, 0, i, 100);
}
```



```
// Shift from blue to green in HSB mode                        9-20
colorMode(HSB, 360, 100, 100);
for (int i = 0; i < 100; i++) {
  float newHue = 200 - (i*1.2);
  stroke(newHue, 70, 80);
  line(i, 0, i, 100);
}
```

Hexadecimal

Hexadecimal (hex) notation is an alternative notation for defining color. This method is popular with designers working on the Web because standards such as HyperText Markup Language (HTML) and Cascading Style Sheets (CSS) use this notation. Hex notation for color encodes each of the numbers from 0 to 255 into a two-digit value using the numbers 0 through 9 and the letters *A* through *F*. In this way three RGB values from 0 to 255 can be written as a single six-digit hex value. A few sample conversions demonstrate this notation:

RGB	Hex
255, 255, 255	#FFFFFF
0, 0, 0	#000000
102, 153, 204	#6699CC
195, 244, 59	#C3F43B
116, 206, 206	#74CECE

Converting color values from RGB to hex notation is not intuitive. Most often, the value is taken from a color selector. For instance, you can copy and paste a hex value from Processing's color selector into your code. When using color values encoded in hex notation, you must place a # before the value to distinguish it within the code.

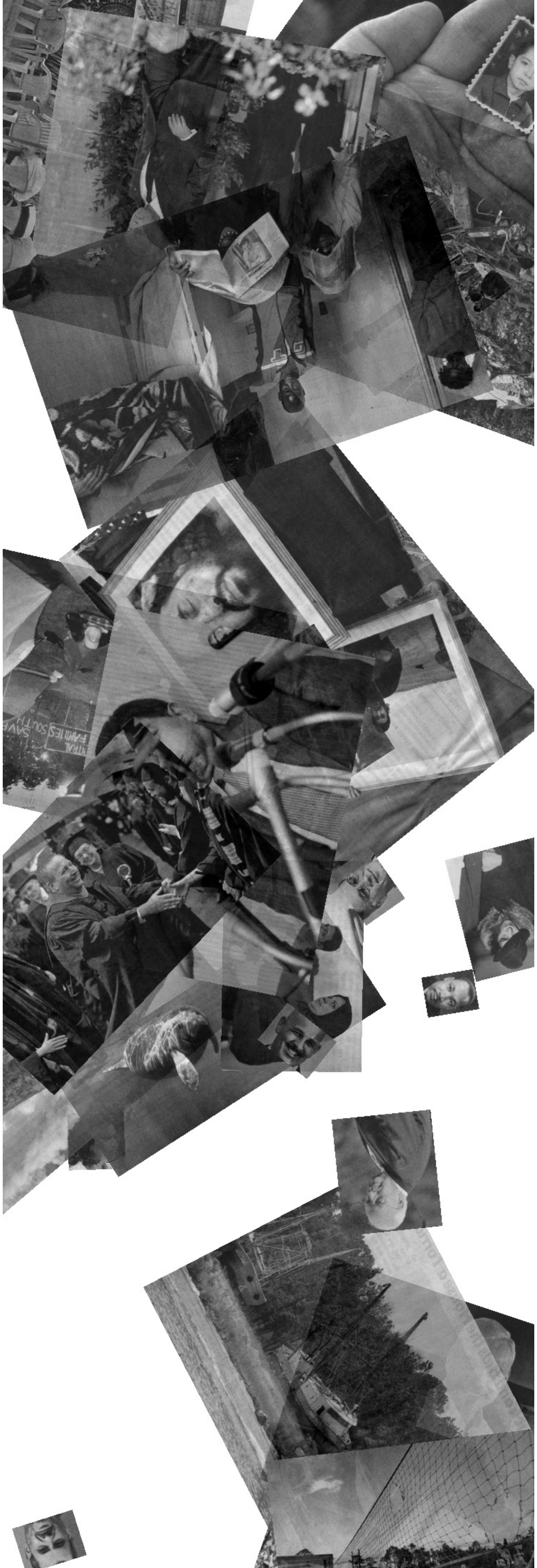
9-21

```
// Code 9-03 rewritten using hex numbers
background(#818257);
noStroke();
fill(#AEDD3C);
rect(17, 17, 66, 66);
```

There's more information about hex notation in Appendix D (p. 669).

Exercises

1. *Explore a wide range of color combinations within one composition.*
2. *Use HSB color and a* `for` *structure to design a gradient between two colors.*
3. *Redraw your composition from exercise 1 using hexadecimal color values.*



Synthesis 1: Form and Code

This unit presents examples of synthesizing concepts from Structure 1 though Transform 2.

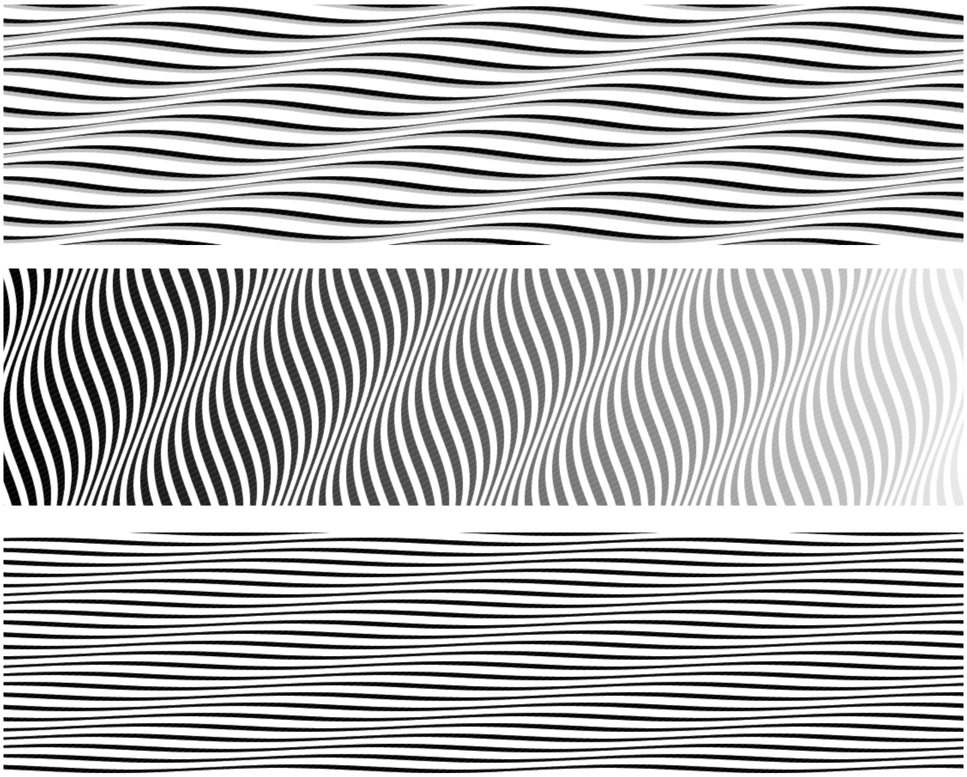
The previous units introduced concepts and techniques including coordinates, drawing with vertices, variables, iteration, conditionals, trigonometry, and transformations. Understanding each of these in isolation is the first step toward learning how to program. Learning how to combine these elements is the second step. There are many ways to combine the components of every programming language for purposes of communication and expression. This programming skill is best acquired through writing more ambitious software and reading more complex programs written by others. This unit introduces four new programs that push beyond those on the previous pages.

Artists and designers throughout the twentieth century practiced the ideas and visual styles currently associated with software culture, long before personal computers became a common tool. The aesthetic legacies of the Bauhaus, art deco, modernist architecture, and op art movements retain a strong voice in contemporary culture, while new forms have emerged through software explorations within the scientific and artistic communities. The programs in this unit reference images from the last hundred years; sampling from Dadaist collage, optical paintings, a twenty-year-old software program, and mathematics.

The software featured in this unit is longer than the brief examples given in this book. It's not practical to print it on these pages, but the code is included in the Processing code download at www.processing.org/learning.

Collage Engine. Reacting to the horror of World War I, European artists and poets within the Dada cultural movement produced works that were deliberately irrational and absurd and that rejected the current standards of art. The poet Tristan Tzara devised a technique for writing that involved taking text from the newspaper, separating the individual words, and putting them back together in random order.

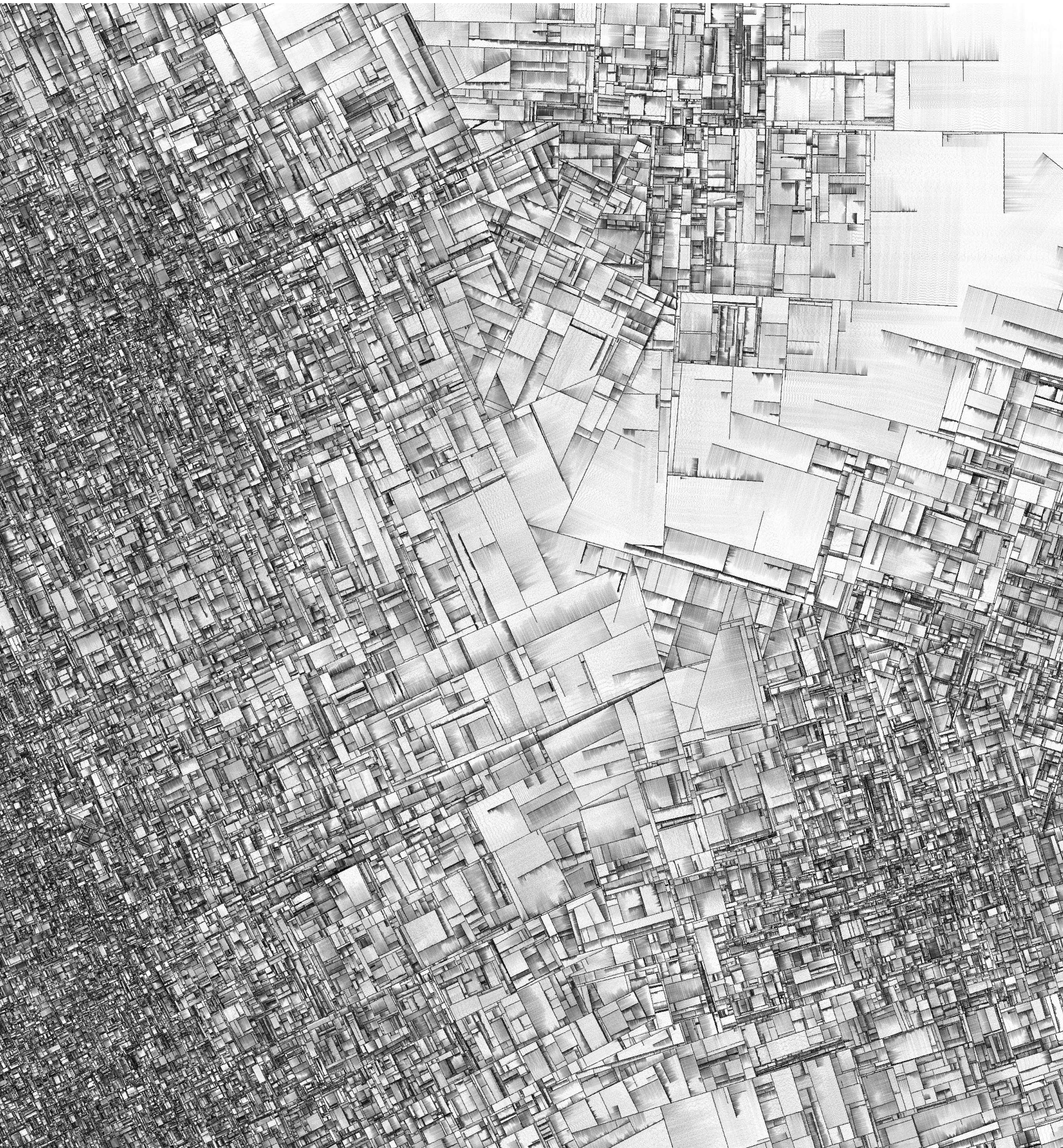
The images shown here were produced using a similar technique with photographs from the first section of *The New York Times* of 9 June 2006. The pictures were cut, scanned, and then repositioned randomly to produce these collages.



Riley Waves. These images were influenced by the paintings of Bridget Riley, a British artist who has exhibited her work since the mid-1960s. Riley's optically vibrant works often have a strong emotional and visceral effect on the viewer. She works exclusively with simple geometric shapes such as curves and lines and constructs visual vibrations through repetition. Because each of the waves in these images transitions from thick to thin, only the `beginShape()` and `endShape()` functions could create them. Like code 14-09 (p. 122), each wave is comprised of a sequence of triangles drawn using the `TRIANGLE_STRIP` parameter.

Interviews 1: Print

Jared Tarbell. *Fractal.Invaders*, *Substrate*
Martin Wattenberg. *Shape of Song*
James Paterson. *The Objectivity Engine*
LettError. RandomFont Beowolf



Fractal.Invaders, Substrate *(Interview with Jared Tarbell)*

Creator	Jared Tarbell
Year	2004
Medium	Software, Prints
Software	Flash, Processing
URL	www.complexification.net

What are *Fractal.Invaders* and *Substrate*?

Fractal.Invaders *and* Substrate *are unique programs that both generate space-filling patterns on a two-dimensional surface. Each uses simplified algorithmic processes to render a more complex whole.*

Fractal.Invaders begins with a rectangular region and recursively fills it with little "invader" objects. Each invader is a combination of black squares arranged in a 5 × 5 grid generated at random during runtime. The only rule of construction requires that the left side of the invader be a mirror copy of the right side. This keeps them laterally symmetric, which endows them with a special attractiveness to the human eye.

There are a total of 32,768 (2^{15}) possible invaders. The magnitude of 15 comes from the product of 3 columns and 5 rows (the last 2 columns of the grid are ignored since they are the same as the first 2). The 2 comes from the fact that each space in the grid can be either black or white.

A small bit of interactivity allows each invader to be clicked. Clicking an invader destroys it, although the empty space left behind is quickly filled with smaller invaders. In this way, the user is ultimately doomed.

Substrate begins similarly with an empty rectangular region. It has been compared to crystal formation and the emergent patterns of urban landscapes. A single line (known internally as a "crack" since the algorithm was inspired by sunbaked mud cracks) begins drawing itself from some random point in some random direction. The line continues to draw itself until it either (a) hits the edge of the screen or (b) hits another line, at which point it stops and two more lines begin. The one simple rule used in the creation of new lines is that they begin at tangents to existing lines. This process is repeated until there are too many lines to keep track of or the program is stopped.

Before writing the program, I only had a vague idea of what it might look like. It wasn't until the first couple of bug-free executions that I realized something incredible was happening. The resulting form was much more complex than the originating algorithm. This particular quality of software is what keeps me interested.

Interesting effects can be created by introducing small variations in the way the first couple of lines are drawn. One of my favorite initial conditions is the creation of three lines, each in its own localized space with a direction that varies from the others by about 30 degrees. After growing for a short time into coherent lattices, they eventually crash into each other, creating an affluence of odd shapes and unexpected mazes.

The watercolor quality of the rendering is achieved by placing large numbers of mostly transparent pixels perpendicular to each line's growth. The trick is to deposit precisely the same

Substrate, 2004. Image courtesy of the artist.

number of pixels regardless of the length of the area being filled. This produces an interesting density modulation across an even mass of pixels.

Why did you create this software?

For me, one of the most enjoyable subjects in computer science is combination. I ask myself a question like, "Given some rules and a few simple objects, how many possible ways can they be combined?" Seldom can I answer this using thought alone, mainly because the complexity of even just a few elements is outside the realm of my imagination. Instead, I write computer programs to solve it for me. Fractal.Invaders *is definitely one of these questions, and is answered completely with the rendering of every single invader. Substrate asks a similar question but with results that, although beautiful, are a little less complete.*

What software tools were used?

For Fractal.Invaders, *I used a combination of Flash and custom software to create and capture the invaders, respectively. In Flash, all work was done using ActionScript. A single symbolic element (black square) exists in the library. Code takes this square and duplicates it hundreds of thousands of times. The entire generative process takes about five minutes to complete, depending on the size of the region to be filled and the speed of the execution. Capturing a high-resolution image of the result is accomplished with a program that scales the Shockwave Flash (SWF) file very large and saves the screen image out to a file.*

Substrate *was created entirely in Processing. Processing was particularly well suited for this as it excels at drawing, especially when dropping millions of deep-color pixels. Processing can also save out extremely large graphic images in an automated fashion. Oftentimes I will run a Processing project overnight. In the morning I awake to a vast collection of unique images, the best of which are archived as print editions.*

Why did you use these tools?

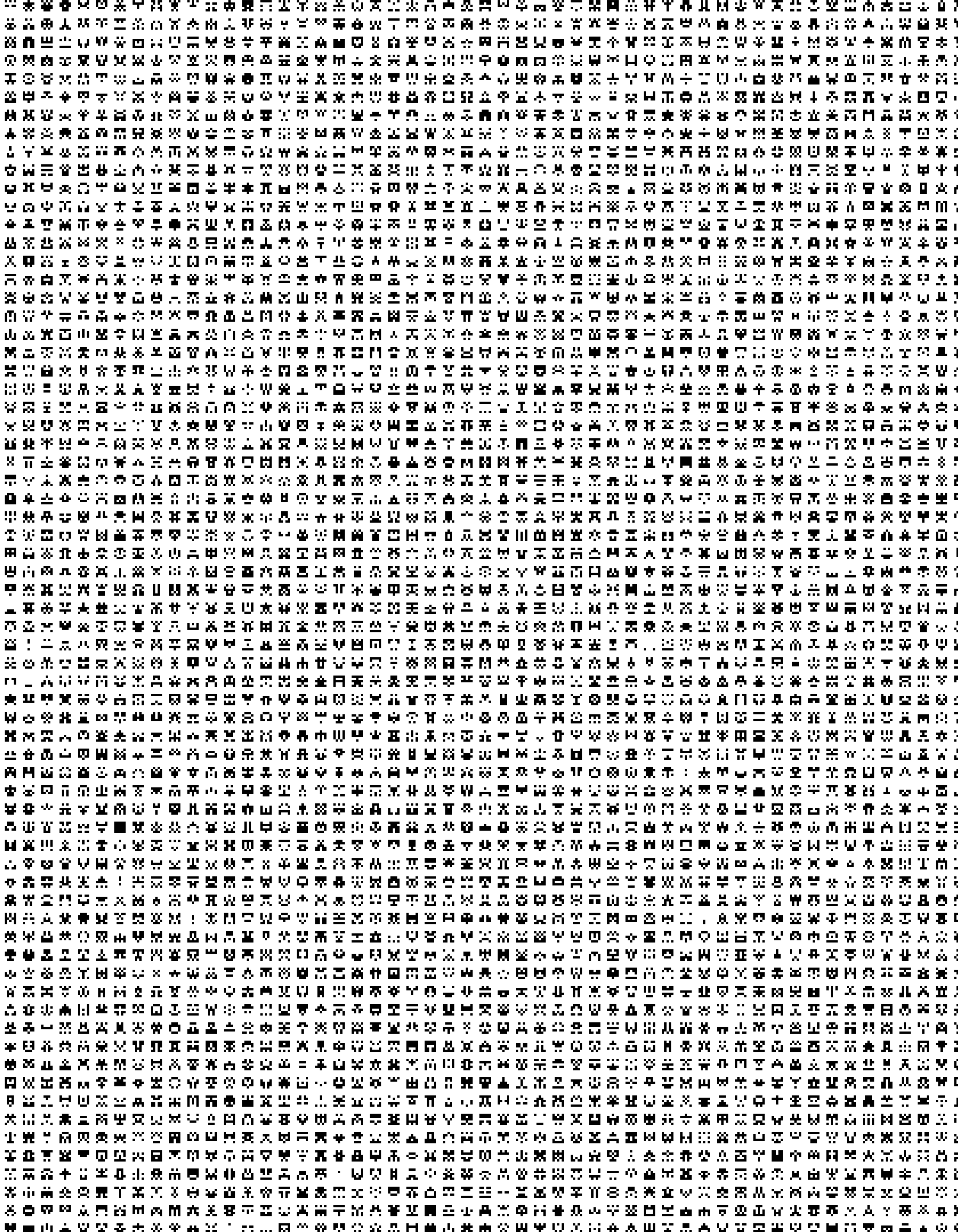
I use Flash because I am comfortable working within it. I use Processing because it enables me to do things Flash simply cannot. Both environments allow me to take a program from concept to completion in a number of hours. Complex visual logic can be built up without the bulky overhead required in more traditional graphic programming languages.

Flash excels at rendering very high resolution images nicely, displaying native vector objects with a high degree of precision and full antialiasing. Processing gives me the computational speed to increase the number of objects in the system by a magnitude of 20 or more. Both programs allow me to produce work that is capable of being viewed by a large number of people worldwide.

Why do you choose to work with software?

With software, anything that can be imagined can be built. Software has a mysterious, undefined border. Programming is truly a process of creating something from nothing. I enjoy most John Maeda's perspective: "While engaged in the deepest trance of coding, all one needs to wish for is any kind of numerical or symbolic resource, and in a flash of lightning it is suddenly there, at your disposal."

Fractal.Invaders, 2004. Image courtesy of the artist.



Input 1: Mouse I

This unit introduces mouse input as a way to control the position and attributes of shapes on screen. It also explains how to change the cursor icon.

Syntax introduced:
`mouseX, mouseY, pmouseX, pmouseY, mousePressed, mouseButton`
`cursor(), noCursor()`

The screen forms a bridge between our bodies and the realm of circuits and electricity inside computers. We control elements on screen through a variety of devices such as touch pads, trackballs, and joysticks, but—aside from the keyboard—the most common input device is the mouse. The computer mouse dates back to the late 1960s when Douglas Engelbart presented the device as an element of the oN-Line System (NLS), one of the first computer systems with a video display. The mouse concept was further developed at the Xerox Palo Alto Research Center (PARC), but its introduction with the Apple Macintosh in 1984 was the catalyst for its current ubiquity. The design of the mouse has gone through many revisions in the last thirty years, but its function has remained the same. In Engelbart's original patent application in 1970 he referred to the mouse as an "X-Y position indicator," and this still accurately, but dryly, defines its contemporary use.

The physical mouse object is used to control the position of the cursor on screen and to select interface elements. The cursor position is read by computer programs as two numbers, the x-coordinate and the y-coordinate. These numbers can be used to control attributes of elements on screen. If these coordinates are collected and analyzed, they can be used to extract higher-level information such as the speed and direction of the mouse. This data can in turn be used for gesture and pattern recognition.

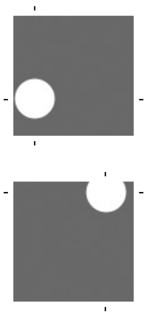
Mouse data

The Processing variables `mouseX` and `mouseY` (note the capital X and Y) store the x-coordinate and y-coordinate of the cursor relative to the origin in the upper-left corner of the display window. To see the actual values produced while moving the mouse, run this program to print the values to the console:

23-01
```
void draw() {
  frameRate(12);
  println(mouseX + " : " + mouseY);
}
```

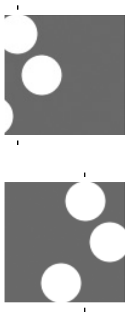
When a program starts, `mouseX` and `mouseY` values are 0. If the cursor moves into the display window, the values are set to the current position of the cursor. If the cursor is at the left, the `mouseX` value is 0 and the value increases as the cursor moves to the right. If the cursor is at the top, the `mouseY` value is 0 and the value increases as the cursor moves down. If `mouseX` and `mouseY` are used in programs without a `draw()` or if `noLoop()` is run in `setup()`, the values will always be 0.

The mouse position is most commonly used to control the location of visual elements on screen. More interesting relations are created when the visual elements relate differently to the mouse values, rather than simply mimicking the current position. Adding and subtracting values from the mouse position creates relationships that remain constant, while multiplying and dividing these values creates changing visual relationships between the mouse position and the elements on the screen. To invert the value of the mouse, simply subtract the `mouseX` value from the width of the window and subtract the `mouseY` value from the height of the screen.



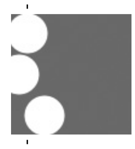
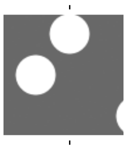
23-02

```
// Circle follows the cursor (the cursor position is
// implied by the crosshairs around the illustration)

void setup() {
  size(100, 100);
  smooth();
  noStroke();
}

void draw() {
  background(126);
  ellipse(mouseX, mouseY, 33, 33);
}
```

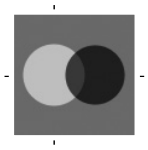
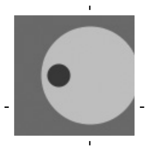


23-03

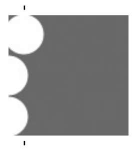
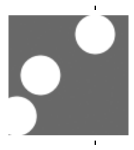
```
// Add and subtract to create offsets

void setup() {
  size(100, 100);
  smooth();
  noStroke();
}

void draw() {
  background(126);
  ellipse(mouseX, 16, 33, 33);     // Top circle
  ellipse(mouseX+20, 50, 33, 33);  // Middle circle
  ellipse(mouseX-20, 84, 33, 33);  // Bottom circle
}
```

```
// Multiply and divide to creates scaling offsets                    23-04

void setup() {
  size(100, 100);
  smooth();
  noStroke();
}

void draw() {
  background(126);
  ellipse(mouseX, 16, 33, 33);    // Top circle
  ellipse(mouseX/2, 50, 33, 33);  // Middle circle
  ellipse(mouseX*2, 84, 33, 33);  // Bottom circle
}
```

```
// Invert cursor position to create a secondary response    23-05

void setup() {
  size(100, 100);
  noStroke();
  smooth();
}

void draw() {
  float x = mouseX;
  float y = mouseY;
  float ix = width - mouseX;   // Inverse X
  float iy = mouseY - height;  // Inverse Y
  background(126);
  fill(255, 150);
  ellipse(x, height/2, y, y);
  fill(0, 159);
  ellipse(ix, height/2, iy, iy);
}
```

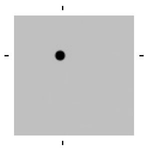
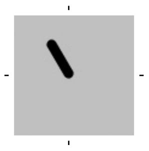



```
// Exponential functions can create nonlinear relations      23-06
// between the mouse and shapes affected by the mouse

void setup() {
  size(100, 100);
  smooth();
  noStroke();
}

void draw() {
  background(126);
  float normX = mouseX / float(width);
  ellipse(mouseX, 16, 33, 33);                    // Top
  ellipse(pow(normX, 4) * width, 50, 33, 33);   // Middle
  ellipse(pow(normX, 8) * width, 84, 33, 33);   // Bottom
}
```

The Processing variables `pmouseX` and `pmouseY` store the mouse values from the previous frame. If the mouse does not move, the values will be the same, but if the mouse is moving quickly there can be large differences between the values. To see the difference, run the following program and alternate moving the mouse slowly and quickly. Watch the values print to the console.

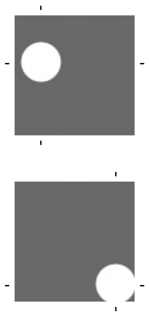
```
void draw() {                                                  23-07
  frameRate(12);
  println(pmouseX - mouseX);
}
```

Drawing a line from the previous mouse position to the current position shows the changing position in one frame, revealing the speed and direction of the mouse. When the mouse is not moving, a point is drawn, but quick mouse movements create long lines.

```
// Draw a line between the current and previous positions     23-08

void setup() {
  size(100, 100);
  strokeWeight(8);
  smooth();
}

void draw() {
  background(204);
  line(mouseX, mouseY, pmouseX, pmouseY);
}
```

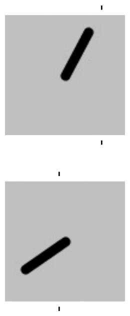
The `mouseX` and `mouseY` values can control translation, rotation, and scale by using them as parameters in the transformation functions. You can move a circle around the screen by changing the parameters to `translate()` rather than by changing the *x* and *y* parameters of `ellipse()`.



23-09

```
// Use translate() to move a shape

void setup() {
  size(100, 100);
  smooth();
  noStroke();
}

void draw() {
  background(126);
  translate(mouseX, mouseY);
  ellipse(0, 0, 33, 33);
}
```

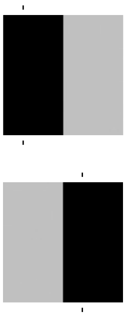
Before using `mouseX` and `mouseY` as parameters to transformation functions, it's important to think first about how they relate to the expected parameters. For example, the `rotate()` function expects its parameters in units of radians (p. 117). To make a shape rotate 360 degrees as the cursor moves from the left edge to the right edge of the window, the values of `mouseX` must be converted to values from 0.0 to 2π. In the following example, the `map()` function is used to make this conversion. The resulting value is used as the parameter to `rotate()` to turn the line as the mouse moves back and forth between the left and right edge of the display window.



23-10

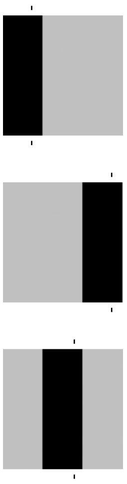
```
// Use rotate() to move a shape

void setup() {
  size(100, 100);
  strokeWeight(8);
  smooth();
}

void draw() {
  background(204);
  float angle = map(mouseX, 0, width, 0, TWO_PI);
  translate(50, 50);
  rotate(angle);
  line(0, 0, 40, 0);
}
```

Using the `mouseX` and `mouseY` variables with an `if` structure allows the cursor to select regions of the screen. The following examples demonstrate the cursor making a selection between different areas of the display window.



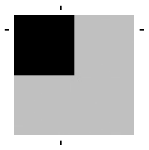
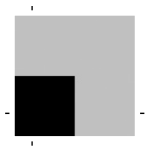
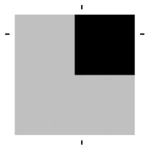
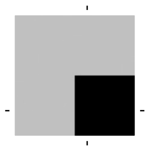
23-11

```
// Cursor position selects the left or right half
// of the display window

void setup() {
  size(100, 100);
  noStroke();
  fill(0);
}

void draw() {
  background(204);
  if (mouseX < 50) {
    rect(0, 0, 50, 100);   // Left
  } else {
    rect(50, 0, 50, 100);  // Right
  }
}
```



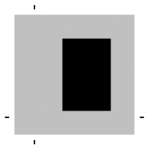
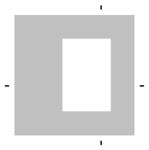
23-12

```
// Cursor position selects the left, middle,
// or right third of the display window

void setup() {
  size(100, 100);
  noStroke();
  fill(0);
}

void draw() {
  background(204);
  if (mouseX < 33) {
    rect(0, 0, 33, 100);   // Left
  } else if ((mouseX >= 33) && (mouseX <= 66)) {
    rect(33, 0, 33, 100);  // Middle
  } else {
    rect(66, 0, 33, 100);  // Right
  }
}
```

23-13

```
// Cursor position selects a quadrant of
// the display window

void setup() {
  size(100, 100);
  noStroke();
  fill(0);
}

void draw() {
  background(204);
  if ((mouseX <= 50) && (mouseY <= 50)) {
    rect(0, 0, 50, 50);    // Upper-left
  } else if ((mouseX <= 50) && (mouseY > 50)) {
    rect(0, 50, 50, 50);   // Lower-left
  } else if ((mouseX > 50) && (mouseY < 50)) {
    rect(50, 0, 50, 50);   // Upper-right
  } else {
    rect(50, 50, 50, 50);  // Lower-right
  }
}
```

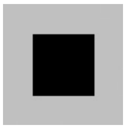
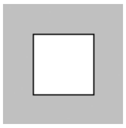



23-14

```
// Cursor position selects a rectangular area to
// change the fill color

void setup() {
  size(100, 100);
  noStroke();
  fill(0);
}

void draw() {
  background(204);
  if ((mouseX > 40) && (mouseX < 80) &&
      (mouseY > 20) && (mouseY < 80)) {
    fill(255);
  } else {
    fill(0);
  }
  rect(40, 20, 40, 60);
}
```

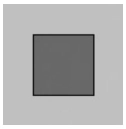
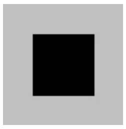
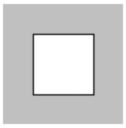
Mouse buttons

Computer mice and other similar input devices typically have between one and three buttons, and Processing can detect when these buttons are pressed. The button status and the cursor position together allow the mouse to perform different actions. For example, pressing a button when the mouse is over an icon can select it, so the icon can be moved to a different location on screen. The `mousePressed` variable is `true` if any mouse button is pressed and `false` if no mouse button is pressed. The variable `mouseButton` is `LEFT`, `CENTER`, or `RIGHT` depending on the mouse button most recently pressed. The `mousePressed` variable reverts to `false` as soon as the button is released, but the `mouseButton` variable retains its value until a different button is pressed. These variables can be used independently or in combination to control your software. Run these programs to see how the software responds to your fingers.

23-15

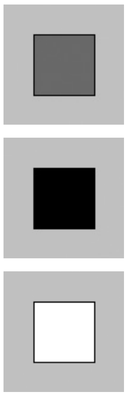
```
// Set the square to white when a mouse button is pressed

void setup() {
  size(100, 100);
}

void draw() {
  background(204);
  if (mousePressed == true) {
    fill(255);  // White
  } else {
    fill(0);    // Black
  }
  rect(25, 25, 50, 50);
}
```

23-16

```
// Set the square to black when the left mouse button
// is pressed and white when the right button is pressed

void setup() {
  size(100, 100);
}

void draw() {
  if (mouseButton == LEFT) {
    fill(0);    // Black
  } else if (mouseButton == RIGHT) {
    fill(255);  // White
  } else {
    fill(126);  // Gray
  }
  rect(25, 25, 50, 50);
}
```

23-16 cont.



23-17

```
// Set the square to black when the left mouse button
// is pressed, white when the right button is pressed,
// and gray when a button is not pressed

void setup() {
  size(100, 100);
}

void draw() {
  if (mousePressed == true) {
    if (mouseButton == LEFT) {
      fill(0);    // Black
    } else if (mouseButton == RIGHT) {
      fill(255);  // White
    }
  } else {
    fill(126);    // Gray
  }
  rect(25, 25, 50, 50);
}
```

Not all mice have multiple buttons, and if software is distributed widely, the interaction should not rely on detecting which button is pressed. For example, if you are posting your work on the Web, don't rely on the middle or right button for using the software because many users won't have a two- or three-button mouse.

Cursor icon

The cursor can be hidden with the `noCursor()` function and can be set to appear as a different icon with the `cursor()` function. When the `noCursor()` function is run, the cursor icon disappears as it moves into the display window. To give feedback about the location of the cursor within the software, a custom cursor can be drawn and controlled with the `mouseX` and `mouseY` variables.

```
// Draw an ellipse to show the position of the hidden cursor          23-18

void setup() {
  size(100, 100);
  strokeWeight(7);
  smooth();
  noCursor();
}

void draw() {
  background(204);
  ellipse(mouseX, mouseY, 10, 10);
}
```

If `noCursor()` is run, the cursor will be hidden while the program is running until the `cursor()` function is run to reveal it.

```
// Hides the cursor until a mouse button is pressed                   23-19

void setup() {
  size(100, 100);
  noCursor();
}

void draw() {
  background(204);
  if (mousePressed == true) {
    cursor();
  }
}
```

Adding a parameter to the `cursor()` function allows it to be changed to another icon. The self-descriptive options for the *MODE* parameter are `ARROW`, `CROSS`, `HAND`, `MOVE`, `TEXT`, and `WAIT`.

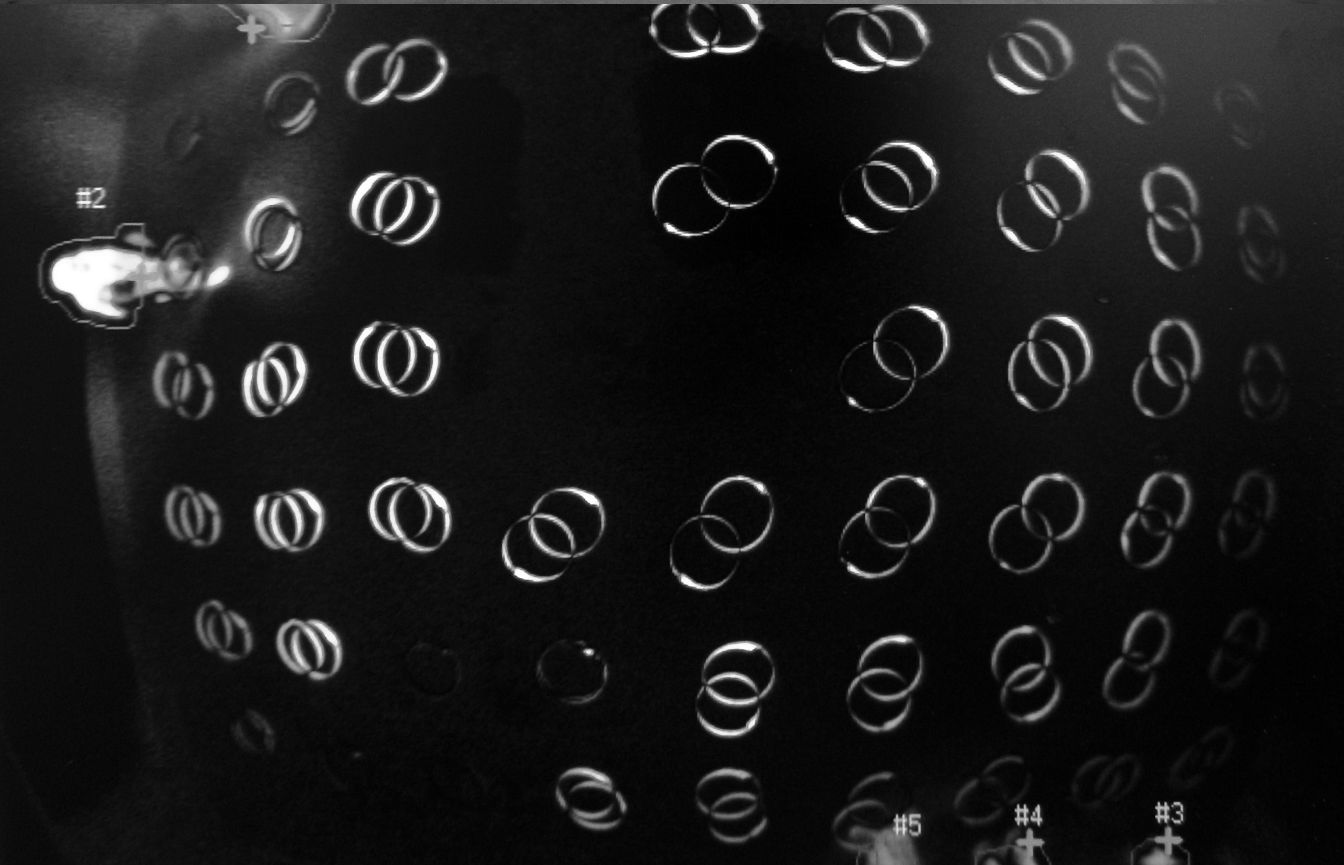
```
// Draws the cursor as a hand when a mouse button is pressed          23-20

void setup() {
  size(100, 100);
  smooth();
}

void draw() {
  background(204);
  if (mousePressed == true) {
    cursor(HAND);
  } else {
    cursor(MOVE);
  }
  line(mouseX, 0, mouseX, height);
  line(0, mouseY, height, mouseY);
}
```

23-20
cont.

These cursor images are part of your computer's operating system and will appear differently on different machines.

Exercises

1. *Control the position of a shape with the mouse. Strive to create a more interesting relation than one directly mimicking the position of the cursor.*
2. *Invent three unique shapes that behave differently in relation to the mouse. Each shape's behavior should change when the mouse is pressed. Relate the form of each shape to its behavior.*
3. *Create a custom cursor that changes as the mouse moves through the display window.*


#2
#5
#4
#3

Extension 3: Vision

Text by Golan Levin

A well-known anecdote relates how, sometime in 1966, the legendary artificial intelligence pioneer Marvin Minsky directed an undergraduate student to solve "the problem of computer vision" as a summer project.[1] This anecdote is often resuscitated to illustrate how egregiously the difficulty of computational vision has been underestimated. Indeed, nearly forty years later the discipline continues to confront numerous unsolved (and perhaps unsolvable) challenges, particularly with respect to high-level "image understanding" issues such as pattern recognition and feature recognition. Nevertheless, the intervening decades of research have yielded a great wealth of well-understood, low-level techniques that are able, under controlled circumstances, to extract meaningful information from a camera scene. These techniques are indeed elementary enough to be implemented by novice programmers at the undergraduate or even high-school level.

Computer vision in interactive art

The first interactive artwork to incorporate computer vision was, interestingly enough, also one of the first interactive artworks. Myron Krueger's legendary *Videoplace*, developed between 1969 and 1975, was motivated by his deeply felt belief that the entire human body ought to have a role in our interactions with computers. In the Videoplace installation, a participant stands in front of a backlit wall and faces a video projection screen. The participant's silhouette is then digitized and its posture, shape, and gestural movements analyzed. In response, *Videoplace* synthesizes graphics such as small "critters" that climb up the participant's projected silhouette, or colored loops drawn between the participant's fingers. Krueger also allowed participants to paint lines with their fingers, and, indeed, entire shapes with their bodies; eventually, *Videoplace* offered more than fifty compositions and interactions. *Videoplace* is notable for many "firsts" in the history of human-computer interaction. Some of its interaction modules allowed two participants in mutually remote locations to participate in the same shared video space, connected across the network—an implementation of the first multiperson virtual reality, or, as Krueger termed it, an "artificial reality." *Videoplace*, it should be noted, was developed before the mouse became the ubiquitous desktop device it is today, and was (in part) created to demonstrate interface alternatives to the keyboard terminals that dominated computing so completely in the early 1970s.

Messa di Voce (p. 511), created by this text's author in collaboration with Zachary Lieberman, uses whole-body vision-based interactions similar to Krueger's, but combines them with speech analysis and situates them within a kind of projection-based

Rafael Lozano-Hemmer. *Standards and Double Standards*, 2004. Images courtesy of the bitforms gallery, nyc.

augmented reality. In this audiovisual performance, the speech, shouts, and songs produced by two abstract vocalists are visualized and augmented in real time by synthetic graphics. To accomplish this, a computer uses a set of vision algorithms to track the locations of the performers' heads; this computer also analyzes the audio signals coming from the performers' microphones. In response, the system displays various kinds of visualizations on a projection screen located just behind the performers; these visualizations are synthesized in ways that are tightly coupled to the sounds being spoken and sung. With the help of the head-tracking system, moreover, these visualizations are projected such that they appear to emerge directly from the performers' mouths.

Rafael Lozano-Hemmer's installation *Standards and Double Standards* (2004) incorporates full-body input in a less direct, more metaphorical context. This work consists of fifty leather belts, suspended at waist height from robotic servomotors mounted on the ceiling of the exhibition room. Controlled by a computer vision-based tracking system, the belts rotate automatically to follow the public, turning their buckles slowly to face passers-by. Lozano-Hemmer's piece "turns a condition of pure surveillance into an 'absent crowd' using a fetish of paternal authority: the belt."[2]

The theme of surveillance plays a foreground role in David Rokeby's *Sorting Daemon* (2003). Motivated by the artist's concerns about the increasing use of automated systems for profiling people as part of the "war on terrorism," this site-specific installation works toward the automatic construction of a diagnostic portrait of its social (and racial) environment. Rokeby writes: "The system looks out onto the street, panning, tilting and zooming, looking for moving things that might be people. When it finds what it thinks might be a person, it removes the person's image from the background. The extracted person is then divided up according to areas of similar colour. The resulting swatches of colour are then organized [by hue, saturation and size] within the arbitrary context of the composite image" projected onsite at the installation's host location.[3]

Another project themed around issues of surveillance is *Suicide Box*, by the Bureau of Inverse Technology (Natalie Jeremijenko and Kate Rich). Presented as a device for measuring the hypothetical "despondency index" of a given locale, the *Suicide Box* nevertheless records very real data regarding suicide jumpers from the Golden Gate Bridge. According to the artists, "The *Suicide Box* is a motion-detection video system, positioned in range of the Golden Gate Bridge, San Francisco, in 1996. It watched the bridge constantly and when it recognized vertical motion, captured it to a video record. The resulting footage displays as a continuous stream the trickle of people who jump off the bridge. The Golden Gate Bridge is the premiere suicide destination in the United States; a 100-day initial deployment period of the *Suicide Box* recorded 17 suicides. During the same time period the Port Authority counted only 13."[4] Elsewhere, Jeremijenko has explained that "the idea was to track a tragic social phenomenon which was not being counted—that is, doesn't count."[5] The *Suicide Box* has met with considerable controversy, ranging from ethical questions about recording the suicides to disbelief that the recordings could be real. Jeremijenko, whose aim is to address the hidden politics of technology, has pointed out that such attitudes express a recurrent theme—"the inherent suspicion of artists working with material evidence"—evidence obtained, in this case, with the help of machine vision-based surveillance.

Considerably less macabre is Christian Möller's clever Cheese installation (2003), which the artist developed in collaboration with the California Institute of Technology and the Machine Perception Laboratories of the University of California, San Diego. Motivated, perhaps, by the culture shock of his relocation to Hollywood, the German-born Möller directed "six actresses to hold a smile for as long as they could, up to one and a half hours. Each ongoing smile is scrutinized by an emotion recognition system, and whenever the display of happiness fell below a certain threshold, an alarm alerted them to show more sincerity."[6] The installation replays recordings of the analyzed video on six flat-panel monitors, with the addition of a fluctuating graphic level-meter to indicate the strength of each actress' smile. The technical implementation of this artwork's vision-based emotion recognition system is quite sophisticated.

As can be seen from these examples, artworks employing computer vision range from the highly formal and abstract to the humorous and sociopolitical. They concern themselves with the activities of willing participants, paid volunteers, or unaware strangers. They track people of interest at a wide variety of spatial scales, from extremely intimate studies of their facial expressions, to the gestures of their limbs, to the movements of entire bodies. The examples above represent just a small selection of notable works in the field and of the ways in which people (and objects) have been tracked and dissected by video analysis. Other noteworthy artworks that use machine vision include Marie Sester's *Access*; Joachim Sauter and Dirk Lüsebrink's *Zerseher* and *Bodymover*; Scott Snibbe's *Boundary Functions* and *Screen Series*; Camille Utterback and Romy Achituv's *TextRain*; Jim Campbell's *Solstice*; Christa Sommerer and Laurent Mignonneau's *A-Volve*; Danny Rozin's *Wooden Mirror*; Chico MacMurtrie's *Skeletal Reflection*, and various works by Simon Penny, Toshio Iwai, and numerous others. No doubt many more vision-based artworks remain to be created, especially as these techniques gradually become incorporated into developing fields like physical computing and robotics.

Elementary computer vision techniques

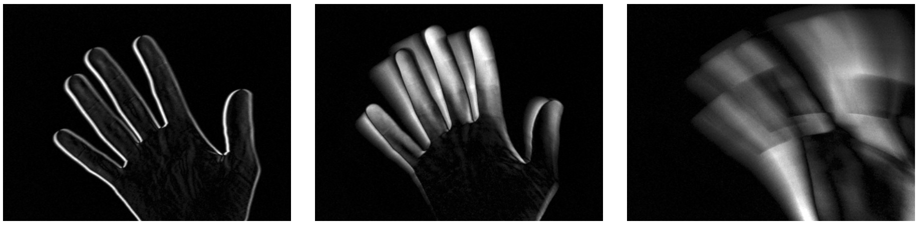
To understand how novel forms of interactive media can take advantage of computer vision techniques, it is helpful to begin with an understanding of the kinds of problems that vision algorithms have been developed to address, and of their basic mechanisms of operation. The fundamental challenge presented by digital video is that it is computationally "opaque." Unlike text, digital video data in its basic form—stored solely as a stream of rectangular pixel buffers—contains no intrinsic semantic or symbolic information. There is no widely agreed upon standard for representing the content of video, in a manner analogous to HTML, XML, or even ASCII for text (though some new initiatives, notably the MPEG-7 description language, may evolve into such a standard in the future). As a result, a computer, without additional programming, is unable to answer even the most elementary questions about whether a video stream contains a person or object, or whether an outdoor video scene shows daytime or nighttime, et cetera. The discipline of computer vision has developed to address this need.

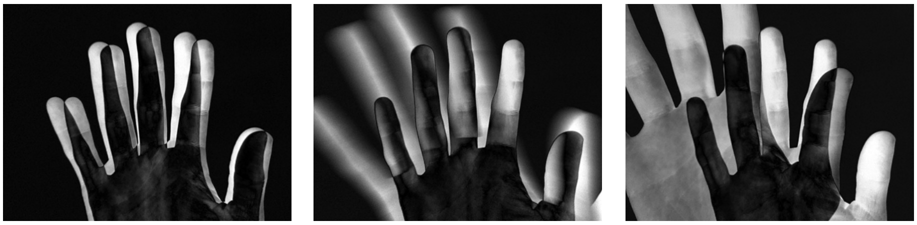
Many low-level computer vision algorithms are geared to the task of distinguishing which pixels, if any, belong to people or other objects of interest in the scene. Three elementary techniques for accomplishing this are frame differencing, which attempts to locate features by detecting their movements; background subtraction, which locates visitor pixels according to their difference from a known background scene; and brightness thresholding, which uses hoped-for differences in luminosity between foreground people and their background environment. These algorithms, described in the following examples, are extremely simple to implement and help constitute a base of detection schemes from which sophisticated interactive systems may be built.

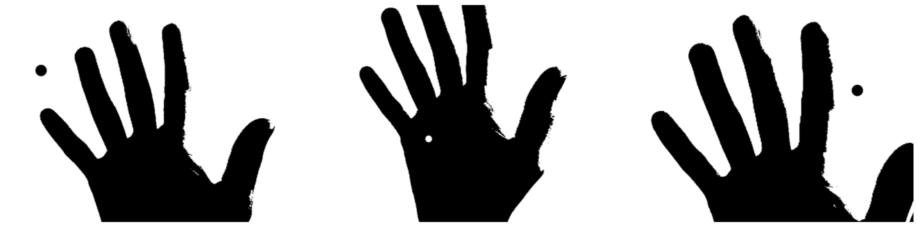
Example 1: Detecting motion (p. 556)
The movements of people (or other objects) within the video frame can be detected and quantified using a straightforward method called frame differencing. In this technique, each pixel in a video frame F1 is compared with its corresponding pixel in the subsequent frame F2. The difference in color and/or brightness between these two pixels is a measure of the amount of movement in that particular location. These differences can be summed across all of the pixels' locations to provide a single measurement of the aggregate movement within the video frame. In some motion detection implementations, the video frame is spatially subdivided into a grid of cells, and the values derived from frame differencing are reported for each of the individual cells. For accuracy, the frame differencing algorithm depends on relatively stable environmental lighting, and on having a stationary camera (unless it is the motion of the camera that is being measured).

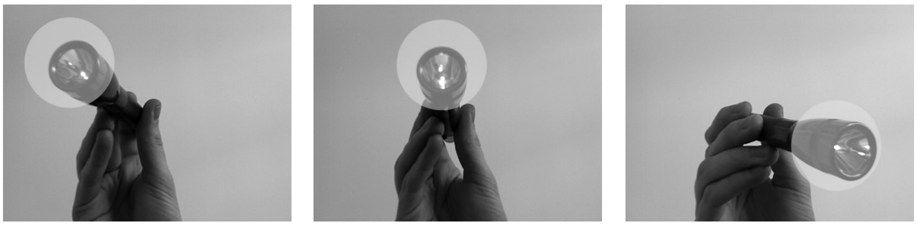
Example 2: Detecting presence (p. 557)
A technique called background subtraction makes it possible to detect the presence of people or other objects in a scene, and to distinguish the pixels that belong to them from those that do not. The technique operates by comparing each frame of video with a stored image of the scene's background, captured at a point in time when the scene was known to be empty. For every pixel in the frame, the absolute difference is computed between its color and that of its corresponding pixel in the stored background image; areas that are very different from the background are likely to represent objects of interest. Background subtraction works well in heterogeneous environments, but it is very sensitive to changes in lighting conditions and depends on objects of interest having sufficient contrast against the background scene.

Example 3: Detection through brightness thresholding (p. 559)
With the aid of controlled illumination (such as backlighting) and/or surface treatments (such as high-contrast paints), it is possible to ensure that objects are considerably darker or lighter than their surroundings. In such cases objects of interest can be distinguished based on their brightness alone. To do this, each video pixel's brightness is compared to a threshold value and tagged accordingly as foreground or background.


Example 1. *Detects motion by comparing each video frame to the previous frame. The change is visualized and is calculated as a number.*


Example 2. *Detects the presence of someone or something in front of the camera by comparing each video frame with a previously saved frame. The change is visualized and is calculated as a number.*


Example 3. *Distinguishes the silhouette of people or objects in each video frame by comparing each pixel to a threshold value. The circle is filled with white when it is within the silhouette.*


Example 4. *Tracks the brightest object in each video frame by calculating the brightest pixel. The light from the flashlight is the brightest element in the frame; therefore, the circle follows it.*

Example 4: Brightness tracking (p. 560)
A rudimentary scheme for object tracking, ideal for tracking the location of a single illuminated point (such as a flashlight), finds the location of the single brightest pixel in every fresh frame of video. In this algorithm, the brightness of each pixel in the incoming video frame is compared with the brightest value yet encountered in that frame; if a pixel is brighter than the brightest value yet encountered, then the location and brightness of that pixel are stored. After all of the pixels have been examined, then the brightest location in the video frame is known. This technique relies on an operational assumption that there is only one such object of interest. With trivial modifications, it can equivalently locate and track the darkest pixel in the scene, or track multiple and differently colored objects.

Of course, many more software techniques exist, at every level of sophistication, for detecting, recognizing, and interacting with people and other objects of interest. Each of the tracking algorithms described above, for example, can be found in elaborated versions that amend its various limitations. Other easy-to-implement algorithms can compute specific features of a tracked object, such as its area, center of mass, angular orientation, compactness, edge pixels, and contour features such as corners and cavities. On the other hand, some of the most difficult to implement algorithms, representing the cutting edge of computer vision research today, are able (within limits) to recognize unique people, track the orientation of a person's gaze, or correctly identify facial expressions. Pseudocodes, source codes, or ready-to-use implementations of all of these techniques can be found on the Internet in excellent resources like Daniel Huber's Computer Vision Homepage, Robert Fisher's HIPR (Hypermedia Image Processing Reference), or in the software toolkits discussed on pages 554-555.

Computer vision in the physical world

Unlike the human eye and brain, no computer vision algorithm is completely general, which is to say, able to perform its intended function given any possible video input. Instead, each software tracking or detection algorithm is critically dependent on certain unique assumptions about the real-world video scene it is expected to analyze. If any of these expectations are not met, then the algorithm can produce poor or ambiguous results or even fail altogether. For this reason, it is essential to design physical conditions in tandem with the development of computer vision code, and to select the software techniques that are most compatible with the available physical conditions.

Background subtraction and brightness thresholding, for example, can fail if the people in the scene are too close in color or brightness to their surroundings. For these algorithms to work well, it is greatly beneficial to prepare physical circumstances that naturally emphasize the contrast between people and their environments. This can be achieved with lighting situations that silhouette the people, or through the use of specially colored costumes. The frame-differencing technique, likewise, fails to detect people if they are stationary. It will therefore have very different degrees of success detecting people in videos of office waiting rooms compared with videos of the Tour de France bicycle race.

A wealth of other methods exist for optimizing physical conditions in order to enhance the robustness, accuracy, and effectiveness of computer vision software. Most are geared toward ensuring a high-contrast, low-noise input image. Under low-light conditions, for example, one of the most helpful such techniques is the use of infrared (IR) illumination. Infrared, which is invisible to the human eye, can supplement the light detected by conventional black-and-white security cameras. Using IR significantly improves the signal-to-noise ratio of video captured in low-light circumstances and can even permit vision systems to operate in (apparently) complete darkness. Another physical optimization technique is the use of retroreflective marking materials, such as those manufactured by 3M Corporation for safety uniforms. These materials are remarkably efficient at reflecting light back toward their source of illumination and are ideal aids for ensuring high-contrast video of tracked objects. If a small light is placed coincident with the camera's axis, objects with retroreflective markers will be detected with tremendous reliability.

Finally, some of the most powerful physical optimizations for machine vision can be made without intervening in the observed environment at all, through well-informed selections of the imaging system's camera, lens, and frame-grabber components. To take one example, the use of a "telecentric" lens can significantly improve the performance of certain kinds of shape-based or size-based object recognition algorithms. For this type of lens, which has an effectively infinite focal length, magnification is nearly independent of object distance. As one manufacturer describes it, "an object moved from far away to near the lens goes into and out of sharp focus, but its image size is constant. This property is very important for gauging three-dimensional objects, or objects whose distance from the lens is not known precisely."[7] Likewise, polarizing filters offer a simple, nonintrusive solution to another common problem in video systems, namely glare from reflective surfaces. And a wide range of video cameras are available, optimized for conditions like high-resolution capture, high-frame-rate capture, short exposure times, dim light, ultraviolet light, and thermal imaging. It pays to research imaging components carefully.

As we have seen, computer vision algorithms can be selected to negotiate best the physical conditions presented by the world, and physical conditions can be modified to be more easily legible to vision algorithms. But even the most sophisticated algorithms and the highest-quality hardware cannot help us find meaning where there is none, or track an object that cannot be described in code. It is therefore worth emphasizing that some visual features contain more information about the world, and are also more easily detected by the computer, than others. In designing systems to "see for us," we must not only become freshly awakened to the many things about the world that make it visually intelligible to us, but also develop a keen intuition about their ease of computability. The sun is the brightest point in the sky, and by its height also indicates the time of day. The mouth cavity is easily segmentable as a dark region, and the circularity of its shape is also closely linked to vowel sound. The pupils of the eyes emit an easy-to-track infrared retroreflection, and they also indicate a person's direction of gaze. Simple frame differencing makes it easy to track motion in a video. The *Suicide Box* (p. 548) uses this technique to dramatic effect.

Tools for computer vision

It can be a rewarding experience to implement machine vision techniques from scratch using code such as the examples provided in this section. To make this possible, the only requirement of one's software development environment is that it should provide direct read-access to the array of video pixels obtained by the computer's frame-grabber. Hopefully, the example algorithms discussed earlier illustrate that creating low-level vision algorithms from first principles isn't so hard. Of course, a vast range of functionality can also be obtained immediately from readily available solutions. Some of the most popular machine vision toolkits take the form of plug-ins or extension libraries for commercial authoring environments geared toward the creation of interactive media. Such plug-ins simplify the developer's problem of connecting the results of the vision-based analysis to the audio, visual, and textual affordances generally provided by such authoring systems.

Many vision plug-ins have been developed for Max/MSP/Jitter, a visual programming environment that is widely used by electronic musicians and VJs. Originally developed at the Parisian IRCAM research center in the mid-1980s and now marketed commercially by the California-based Cycling'74 company, this extensible environment offers powerful control of (and connectivity between) MIDI devices, real-time sound synthesis and analysis, OpenGL-based 3D graphics, video filtering, network communications, and serial control of hardware devices. The various computer vision plug-ins for Max/MSP/Jitter, such as David Rokeby's SoftVNS, Eric Singer's Cyclops, and Jean-Marc Pelletier's CV.Jit, can be used to trigger any Max processes or control any system parameters. Pelletier's toolkit, which is the most feature-rich of the three, is also the only one that is freeware. CV.Jit provides abstractions to assist users in tasks such as image segmentation, shape and gesture recognition, and motion tracking, as well as educational tools that outline the basics of computer vision techniques.

Some computer vision toolkits take the form of stand-alone applications and are designed to communicate the results of their analyses to other environments (such as Processing, Director, or Max) through protocols like MIDI, serial RS-232, UDP, or TCP/IP networks. BigEye, developed by the STEIM (Studio for Electro-Instrumental Music) group in Holland, is a simple and inexpensive example. BigEye can track up to 16 objects of interest simultaneously, according to their brightness, color, and size. The software allows for a simple mode of operation in which the user can quickly link MIDI messages to many object parameters, such as position, speed, and size. Another example is the powerful EyesWeb open platform, a free system developed at the University of Genoa. Designed with a special focus on the analysis and processing of expressive gesture, EyesWeb includes a collection of modules for real-time motion tracking and extraction of movement cues from human full-body movement; a collection of modules for analysis of occupation of 2D space; and a collection of modules for extraction of features from trajectories in 2D space. EyesWeb's extensive vision affordances make it highly recommended for students.

The most sophisticated toolkits for computer vision generally demand greater familiarity with digital signal processing, and they require developers to program in compiled languages like C++ rather than languages like Java, Lingo, or Max. The Intel Integrated Performance Primitives (IPP) library, for example, is among the most general commercial solutions available for computers with Intel-based CPUs. The OpenCV library, by contrast, is a free, open source toolkit with nearly similar capabilities and a tighter focus on commonplace computer vision tasks. The capabilities of these tools, as well as all of those mentioned above, are continually evolving.

Processing includes a basic video library that handles getting pixel information from a camera or movie file as demonstrated in the examples included with this text. The computer vision capabilities of Processing are extended by libraries like Myron, which handles video input and has basic image processing capabilities. Other libraries connect Processing to EyesWeb and OpenCV. They can be found on the libraries page of the Processing website: *www.processing.org/reference/libraries*.

Conclusion

Computer vision algorithms are increasingly used in interactive and other computer-based artworks to track people's activities. Techniques exist that can create real-time reports about people's identities, locations, gestural movements, facial expressions, gait characteristics, gaze directions, and other attributes. Although the implementation of some vision algorithms requires advanced understanding of image processing and statistics, a number of widely used and highly effective techniques can be implemented by novice programmers in as little as an afternoon. For artists and designers who are familiar with popular multimedia authoring systems like Macromedia Director and Max/MSP/Jitter, a wide range of free and commercial toolkits are also available that provide ready access to more advanced vision functionalities.

Since the reliability of computer vision algorithms is limited according to the quality of the incoming video scene and the definition of a scene's quality is determined by the specific algorithms that are used to analyze it, students approaching computer vision for the first time are encouraged to apply as much effort to optimizing their physical scenario as they do their software code. In many cases, a cleverly designed physical environment can permit the tracking of phenomena that might otherwise require much more sophisticated software. As computers and video hardware become more available, and software-authoring tools continue to improve, we can expect to see the use of computer vision techniques increasingly incorporated into media-art education and into the creation of games, artworks, and many other applications.

Notes

1. http://mechanism.ucsd.edu/~bill/research/mercier/2ndlecture.pdf.
2. http://www.fundacion.telefonica.com/at/rlh/eproyecto.html.

3. http://homepage.mac.com/davidrokeby/sorting.html.
4. http://www.bureauit.org/sbox.
5. http://www.wired.com/news/culture/0,1284,64720,00.html.
6. http://www.christian-moeller.com.
7. http://www.mellesgriot.com/pdf/pg11-19.pdf.

Code

Video can be captured into Processing from USB cameras, IEEE 1394 cameras, or video cards with composite or S-video input devices. The examples that follow assume you already have a camera working with Processing. Before trying these examples, first get the examples included with the Processing software to work. Sometimes you can plug a camera into your computer and it will work immediately. Other times it's a difficult process involving trial-and-error changes. It depends on the operating system, the camera, and how the computer is configured. For the most up-to-date information, refer to the Video reference on the Processing website: *www.processing.org/reference/libraries*.

Example 1: Detecting motion

```
// Quantify the amount of movement in the video frame using frame-differencing

import processing.video.*;

int numPixels;
int[] previousFrame;
Capture video;

void setup(){
  size(640, 480);  // Change size to 320 x 240 if too slow at 640 x 480
  video = new Capture(this, width, height, 24);
  numPixels = video.width * video.height;
  // Create an array to store the previously captured frame
  previousFrame = new int[numPixels];
}

void draw() {
  if (video.available()) {
    // When using video to manipulate the screen, use video.available() and
    // video.read() inside the draw() method so that it's safe to draw to the screen
    video.read();        // Read the new frame from the camera
    video.loadPixels();  // Make its pixels[] array available

    int movementSum = 0; // Amount of movement in the frame
    loadPixels();

    for (int i = 0; i < numPixels; i++) {  // For each pixel in the video frame...
```

```
      color currColor = video.pixels[i];
      color prevColor = previousFrame[i];

      // Extract the red, green, and blue components from current pixel
      int currR = (currColor >> 16) & 0xFF;  // Like red(), but faster (see p. 673)
      int currG = (currColor >> 8) & 0xFF;
      int currB =  currColor & 0xFF;

      // Extract red, green, and blue components from previous pixel
      int prevR = (prevColor >> 16) & 0xFF;
      int prevG = (prevColor >> 8) & 0xFF;
      int prevB = prevColor & 0xFF;

      // Compute the difference of the red, green, and blue values
      int diffR = abs(currR - prevR);
      int diffG = abs(currG - prevG);
      int diffB = abs(currB - prevB);

      // Add these differences to the running tally
      movementSum += diffR + diffG + diffB;
      // Render the difference image to the screen
      pixels[i] = color(diffR, diffG, diffB);
      // The following line is much faster, but more confusing to read
      //pixels[i] = 0xff000000 | (diffR << 16) | (diffG << 8) | diffB;
      // Save the current color into the 'previous' buffer
      previousFrame[i] = currColor;
    }

    // To prevent flicker from frames that are all black (no movement),
    // only update the screen if the image has changed.
    if (movementSum > 0) {
      updatePixels();
      println(movementSum);  // Print the total amount of movement to the console
    }
  }
}
```

Example 2: Detecting presence

```
// Detect the presence of people and objects in the frame using a simple
// background-subtraction technique. To initialize the background, press a key.

import processing.video.*;

int numPixels;
int[] backgroundPixels;
Capture video;

void setup() {
  size(640, 480);  // Change size to 320 x 240 if too slow at 640 x 480
  video = new Capture(this, width, height, 24);
  numPixels = video.width * video.height;
  // Create array to store the background image
  backgroundPixels = new int[numPixels];
  // Make the pixels[] array available for direct manipulation
  loadPixels();
}

void draw() {
  if (video.available()) {
    video.read();        // Read a new video frame
    video.loadPixels();  // Make the pixels of video available

    // Difference between the current frame and the stored background
    int presenceSum = 0;

    for (int i = 0; i < numPixels; i++) {  // For each pixel in the video frame...
      // Fetch the current color in that location, and also the color
      // of the background in that spot
      color currColor = video.pixels[i];
      color bkgdColor = backgroundPixels[i];

      // Extract the red, green, and blue components of the current pixel's color
      int currR = (currColor >> 16) & 0xFF;
      int currG = (currColor >> 8) & 0xFF;
      int currB = currColor & 0xFF;

      // Extract the red, green, and blue components of the background pixel's color
      int bkgdR = (bkgdColor >> 16) & 0xFF;
      int bkgdG = (bkgdColor >> 8) & 0xFF;
      int bkgdB = bkgdColor & 0xFF;

      // Compute the difference of the red, green, and blue values
      int diffR = abs(currR - bkgdR);
      int diffG = abs(currG - bkgdG);
      int diffB = abs(currB - bkgdB);

      // Add these differences to the running tally
      presenceSum += diffR + diffG + diffB;
      // Render the difference image to the screen
      pixels[i] = color(diffR, diffG, diffB);
      // The following line does the same thing much faster, but is more technical
      //pixels[i] = 0xFF000000 | (diffR << 16) | (diffG << 8) | diffB;
    }
    updatePixels();        // Notify that the pixels[] array has changed
    println(presenceSum);  // Print out the total amount of movement
  }
}

// When a key is pressed, capture the background image into the backgroundPixels
// buffer by copying each of the current frame's pixels into it.
void keyPressed() {
  video.loadPixels();
  arraycopy(video.pixels, backgroundPixels);
}
```

Example 3: Detection through brightness thresholding

```
// Determines whether a test location (such as the cursor) is contained within
// the silhouette of a dark object

import processing.video.*;

color black = color(0);
color white = color(255);
int numPixels;
Capture video;

void setup() {
  size(640, 480);  // Change size to 320 x 240 if too slow at 640 x 480
  strokeWeight(5);
  video = new Capture(this, width, height, 24);
  numPixels = video.width * video.height;
  noCursor();
  smooth();
}

void draw() {
  if (video.available()) {
    video.read();
    video.loadPixels();
    int threshold = 127;    // Set the threshold value
    float pixelBrightness;  // Declare variable to store a pixel's color

    // Turn each pixel in the video frame black or white depending on its brightness
    loadPixels();
    for (int i = 0; i < numPixels; i++) {
      pixelBrightness = brightness(video.pixels[i]);
      if (pixelBrightness > threshold) {  // If the pixel is brighter than the
        pixels[i] = white;                // threshold value, make it white
      } else {                            // Otherwise,
        pixels[i] = black;                // make it black
      }
    }
    updatePixels();

    // Test a location to see where it is contained. Fetch the pixel at the test
    // location (the cursor), and compute its brightness
    int testValue = get(mouseX, mouseY);
    float testBrightness = brightness(testValue);
    if (testBrightness > threshold) {     // If the test location is brighter than
      fill(black);                        // the threshold set the fill to black
    } else {                              // Otherwise,
      fill(white);                        // set the fill to white
    }
    ellipse(mouseX, mouseY, 20, 20);
  }
}
```

Example 4: Brightness tracking

```
// Tracks the brightest pixel in a live video signal

import processing.video.*;

Capture video;

void setup(){
  size(640, 480);  // Change size to 320 x 240 if too slow at 640 x 480
  video = new Capture(this, width, height, 30);
  noStroke();
  smooth();
}

void draw() {
  if (video.available()) {
    video.read();
    image(video, 0, 0, width, height);  // Draw the webcam video onto the screen

    int brightestX = 0;         // X-coordinate of the brightest video pixel
    int brightestY = 0;         // Y-coordinate of the brightest video pixel
    float brightestValue = 0;  // Brightness of the brightest video pixel

    // Search for the brightest pixel: For each row of pixels in the video image and
    // for each pixel in the yth row, compute each pixel's index in the video
    video.loadPixels();
    int index = 0;
    for (int y = 0; y < video.height; y++) {
      for (int x = 0; x < video.width; x++) {
        // Get the color stored in the pixel
        int pixelValue = video.pixels[index];
        // Determine the brightness of the pixel
        float pixelBrightness = brightness(pixelValue);
        // If that value is brighter than any previous, then store the
        // brightness of that pixel, as well as its (x,y) location
        if (pixelBrightness > brightestValue){
          brightestValue = pixelBrightness;
          brightestY = y;
          brightestX = x;
        }
        index++;
      }
    }

    // Draw a large, yellow circle at the brightest pixel
    fill(255, 204, 0, 128);
    ellipse(brightestX, brightestY, 200, 200);
  }
}
```

Resources

Computer vision software toolkits

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Code Index

This index contains all of the Processing language elements introduced within this book. The page numbers refer to the first use.

Index

This index contains mostly people, software, artwork, and programming languages. For topics, see the table of contents (pp. vii–xvii); for code, see the Code Index.