THE
SYSTEMS
PROGRAMMING
SERIES

Computer Graphics: Principles and Practice

Second Edition

Foley ♦ van Dam ♦ Feiner ♦ Hughes

SECOND EDITION

Computer Graphics

PRINCIPLES AND PRACTICE

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ADDISON-WESLEY PUBLISHING COMPANY
Reading, Massachusetts • Menlo Park, California • New York
Don Mills, Ontario • Wokingham, England • Amsterdam • Bonn
Sydney • Singapore • Tokyo • Madrid • San Juan

Sponsoring Editor: Keith Wollman
Production Supervisor: Bette J. Aaronson
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Illustrators: C&C Associates
Cover Designer: Marshall Henrichs
Manufacturing Manager: Roy Logan

This book is in the **Addison-Wesley Systems Programming Series**
Consulting editors: IBM Editorial Board

Library of Congress Cataloging-in-Publication Data
Computer graphics: principles and practice/James D. Foley . . . [et al.].—2nd ed.
p. cm.
Includes bibliographical references.
ISBN 0-201-12110-7
1. Computer graphics. I. Foley, James D., 1942–.
T385.C587 1990
006.6—dc20 89-35281
CIP

Cover: "Dutch Interior," after Vermeer, by J. Wallace, M. Cohen, and D. Greenberg, Cornell University (Copyright © 1987 Cornell University, Program of Computer Graphics.)

ABCDEFGHIJ-DO-943210

13 Achromatic and Colored Light

The growth of raster graphics has made color and gray scale an integral part of contemporary computer graphics. Color is an immensely complex subject, one that draws on concepts and results from physics, physiology, psychology, art, and graphic design. Many researchers' careers have been fruitfully devoted to developing theories, measurement techniques, and standards for color. In this chapter, we introduce some of the areas of color that are most relevant to computer graphics.

The color of an object depends not only on the object itself, but also on the light source illuminating it, on the color of the surrounding area, and on the human visual system. Furthermore, some objects reflect light (wall, desk, paper), whereas others also transmit light (cellophane, glass). When a surface that reflects only pure blue light is illuminated with pure red light, it appears black. Similarly, a pure green light viewed through glass that transmits only pure red will also appear black. We postpone some of these issues by starting our discussion with achromatic sensations—that is, those described as black, gray, and white.

13.1 ACHROMATIC LIGHT

Achromatic light is what we see on a black-and-white television set or display monitor. An observer of achromatic light normally experiences none of the sensations we associate with red, blue, yellow, and so on. Quantity of light is the only attribute of achromatic light. Quantity of light can be discussed in the physics sense of energy, in which case the terms *intensity* and *luminance* are used, or in the psychological sense of perceived intensity, in which case the term *brightness* is used. As we shall discuss shortly, these two concepts are related but are not the same. It is useful to associate a scalar with different intensity levels, defining 0 as black and 1 as white; intensity levels between 0 and 1 represent different grays.

A black-and-white television can produce many different intensities at a single pixel position. Line printers, pen plotters, and electrostatic plotters produce only two levels: the white (or light gray) of the paper and the black (or dark gray) of the ink or toner deposited on the paper. Certain techniques, discussed in later sections, allow such inherently *bilevel* devices to produce additional intensity levels.

13.1.1 Selecting Intensities—Gamma Correction

Suppose we want to display 256 different intensities. Which 256 intensity levels should we use? We surely do not want 128 in the range of 0 to 0.1 and 128 more in the range of 0.9 to 1.0, since the transition from 0.1 to 0.9 would certainly appear discontinuous. We might initially distribute the levels evenly over the range 0 to 1, but this choice ignores an important characteristic of the eye: that it is sensitive to ratios of intensity levels rather than to absolute values of intensity. That is, we perceive the intensities 0.10 and 0.11 as differing just as much as the intensities 0.50 and 0.55. (This nonlinearity is easy to observe: Cycle through the settings on a three-way 50–100–150-watt lightbulb; you will see that the step from 50 to 100 seems much greater than the step from 100 to 150.) On a brightness (that is, perceived intensity) scale, the differences between intensities of 0.10 and 0.11 and between intensities of 0.50 and 0.55 are equal. Therefore, the intensity levels should be spaced logarithmically rather than linearly, to achieve equal steps in brightness.

To find 256 intensities starting with the lowest attainable intensity I_0 and going to a maximum intensity of 1.0, with each intensity r times higher than the preceding intensity, we use the following relations:

$$I_0 = I_0,\ I_1 = rI_0,\ I_2 = rI_1 = r^2 I_0,\ I_3 = rI_2 = r^3 I_0,\ \ldots,\ I_{255} = r^{255} I_0 = 1. \quad (13.1)$$

Therefore,

$$r = (1/I_0)^{1/255},\ I_j = r^j I_0 = (1/I_0)^{j/255}\, I_0 = I_0^{(255-j)/255} \quad \text{for } 0 \le j \le 255, \quad (13.2)$$

and in general for $n + 1$ intensities,

$$r = (1/I_0)^{1/n},\ I_j = I_0^{(n-j)/n} \quad \text{for } 0 \le j \le n. \quad (13.3)$$

With just four intensities ($n = 3$) and an I_0 of $\frac{1}{8}$ (an unrealistically large value chosen for illustration only), Eq. (13.3) tells us that $r = 2$, yielding intensity values of $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, and 1.

The minimum attainable intensity I_0 for a CRT is anywhere from about $\frac{1}{200}$ up to $\frac{1}{40}$ of the maximum intensity of 1.0. Therefore, typical values of I_0 are between 0.005 and 0.025. The minimum is not 0, because of light reflection from the phosphor within the CRT. The ratio between the maximum and mimimum intensities is called the *dynamic range*. The exact value for a specific CRT can be found by displaying a square of white on a field of black and measuring the two intensities with a photometer. This measurement is taken in a completely darkened room, so that reflected ambient light does not affect the intensities. With an I_0 of 0.02, corresponding to a dynamic range of 50, Eq. (13.2) yields $r =$ 1.0154595 . . ., and the first few and last two intensities of the 256 intensities from Eq. (13.1) are 0.0200, 0.0203, 0.0206, 0.0209, 0.0213, 0.0216, . . ., 0.9848, 1.0000.

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