Visual Computing: Geometry, Graphics, and Vision

Visual Computing: Geometry, Graphics, and Vision

Frank Nielsen

CHARLES RIVER MEDIA, INC.
Hingham, Massachusetts

Publisher: Jenifer Niles
Cover Design: Tyler Creative
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CHARLES RIVER MEDIA, INC.
10 Downer Avenue
Hingham, Massachusetts 02043
781-740-0400 / 781-740-8816 (FAX)
info@charlesriver.com / www.charlesriver.com

This book is printed on acid-free paper.

Frank Nielsen. Visual Computing: Geometry, Graphics, and Vision.
ISBN: 1-58450-427-7

Library of Congress Cataloging-in-Publication Data

```
Nielsen, Frank.
  Visual computing : geometry, graphics, and vision / Frank Nielsen.
       p. cm. Includes index.
  ISBN 1-58450-427-7 (hc. : alk. paper)
 1.  Computer graphics. 2.  Visual programming (Computer science)
 3.  Computer vision. 4.  Geometry--Data processing.  I. Title.
  T385.N519 2005
  006.6--dc22                                        2005010610
```

Printed in the United States of America
05 7 6 5 4 3 2 First Edition

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To my family,
To Audrey 玲奈 *and Julien* 怜旺

Ariel by Audrey (3 years old)

Contents

Foreword

I am really excited to be able to write a foreword to Frank Nielsen's new book *Visual Computing: Geometry, Graphics, and Vision.* The fusion of computer graphics, computer vision, computational geometry, and discrete algorithms that this book presents is truly unique and, in afterthought, so obvious. Geometry, graphics, and vision all deal in some form with the shape of objects, their motions, as well as the transport of light and its interaction with objects—yet historically they have been covered by separate courses in curricula, grown around a distinct set of conferences, and cultivated separate communities. This book clearly shows how much they have in common and the kinds of synergies that occur when a common core of material is presented in a way that both serves and is enriched by all three disciplines.

Take coordinates and coordinate transforms as a simple example. Everyone needs the common math: homogeneous coordinates, matrix representations for transformations, quaternion representations for 3D rotations, parametrizations for other flats such as lines in 3-space, and so on. In a graphics course, transform hierarchies in modeling, or clipping and projection transforms for viewing may get more attention. In computer vision, epipolar geometry and the relations among multiple projections may get special treatment. In computational geometry, Plücker coordinates for lines in 3D may be studied to prepare for problems in stabbing and visibility. Yet every one of these topics can be very useful in each of the three disciplines: image-based rendering needs the math of multiview geometry, indexing lightfields requires the geometry of lines in space, and clipping is an essential geometric computation problem. The *Visual Computing* book manages to cover all three points of view in a coherent yet concise way, to the benefit of all sides.

I have taught an algorithms course for over a decade now and topics like dictionaries and priority queues are its bread-and-butter. It was truly refreshing to see these same topics introduced early in this book, but with novel effective examples all motivated by visual computing. The same happens later on with randomization, a topic that has been seriously studied across all these communities, but with different emphases. This text truly establishes bridges where they will make the most impact: early on in a student's education. I can see this book being used for a separate integrated course of its own, or as a supplement to existing courses and other texts covering algorithms, computational geometry, computer graphics, or computer vision—thus providing a fruitful common ground between what are currently separate offerings.

The book can also benefit graduate students and researchers across all parts of computer science that deal with modeling or interacting with the physical world. The material is methodically organized, the exposition is rigorous yet well-motivated with plenty of instructive examples. Major techniques and algorithms are given in actual C++ code, and these programs and additional materials are available on a companion Web site. Additional references to the literature are given at the end of each chapter.

Leonidas J. Guibas
Professor of Geometric Computing
Computer Science Department
Stanford University

May 2005

Acknowledgments

I would like to thank my friends, colleagues, and peers who took time to review portions of the manuscript: Paul Agron (State University of New York at Stony Brook, USA), Pierre Alliez (INRIA, France), Hervé Brönnimann (Polytechnic University, USA), Patrick Degener (University of Bonn, Germany), Olivier Devillers (INRIA, France), Richard Nock (DSI-GRIMAAG UAG, France), Stéphane Nullans (Realviz, France), Shigeru Owada (University of Tokyo/Sony Computer Science Laboratories Inc., Japan), Sylvain Pion (INRIA, France), Mariette Yvinec (INRIA, France) and Imad Zoghlami (Siemens Corporate Research, USA).

I am particularly indebted to my colleagues Dr. Shigeru Owada who got the very early draft, and Pr. Richard Nock who was my first alpha release reader.

I would like to heartfully thank the following people and organizations for their kind image contributions: Bart Adams (KU Leuven, Belgium), Sue Addleman (Cyberware, USA), Pravin Bhat (Washington University, USA), Pierre Alliez (INRIA, France), Yuji Ayatsuka (Sony Computer Science Laboratories Inc., Japan), Patrick Coleman (University of Toronto, Canada), Patrick Degener (University of Bonn, Germany), Greg Downing (Consultant, USA), Heather Gentner (Stanford University, USA), David Xianfeng Gu (State University of New York at Stony Brook, USA), Stéphane Guy (INRIA, France), Sayed Ibrahim Hashimi (University of Florida, USA), Stephen Ingram (Emory University, USA), SpherOnVR (Thomas Köllig, Germany), Bruno Lévy (INRIA, France), Shengyou Lin (Zhejiang University, China), Stefan Maierhofer (Vienna University of Technology, Austria), Martin Marinov (RWTH Aachen, Germany), Pascal Müller (ETH Zurich, Switzerland), Stéphane Nullans (Realviz, France), Konrad Polthier (Zuse Institute Berlin, Germany), Christian Rochefort (InSpeck, Canada), Steven M. Seitz (University of Washington, USA), Junichi Rekimoto (Sony Computer Science Laboratories Inc., Japan), Greg Turk (Georgia Institute of Technology, USA), Emma Wixey (Vicon Motion Systems, USA) and Jingyi Yu (MIT, USA).

Unfortunately, sometimes for copyright reasons, I could not use some images I received. Nevertheless, I would like to acknowledge Sumanta Pattanaik (University of Central Florida, USA), Paul Rademacher (Dreamworks Animation, USA), and Szymon Rusinkiewicz (Princeton University, USA) for kindly providing me with such material. I also thank Professor Marc Levoy (CS, Stanford University) for letting me use the 3D models (mostly the `bunny` model) of the Stanford 3D scanning repository models in the illustrations.

I am deeply honored that Professor Leonidas J. Guibas has kindly accepted to write the foreword.

This book became possible thanks to the warm encouragements and supports from Sony Computer Science Laboratories, Inc. I express my gratitude to Dr. Mario Tokoro and Dr. Hiroaki Kitano, as well as all other members of Sony Computer Science Laboratories Inc. (as known as Sony CSL for short). Last but not least, during this book project I particularly enjoyed lunch breaks with my colleague Dr. Yosuke Tamura who showed much interest in my writing progress!

Further, I would like to extend my thanks to Jenifer Niles who was my principal contact at Charles River Media. Jenifer with her team (Bryan Davidson, Lance Morganelli, Meg Dunkerley, and the copyeditor) managed to get the book ready much before I anticipated!

I apologize for any (involuntary) name omission and remaining errors. As Blaise Pascal said,[1] I have written you a thick book because I did not have time to write a short one.

Finally, my deepest thanks and love go to my family for their everlasting support.

Tokyo, Japan F. N.
May 2005.

[1] "I have written you a long letter because I did not have time to write a short one."

Notational Conventions

The following is a brief review of the mathematical notations used throughout the book.

Scalar Numbers & Ranges:

a, α, λ, u_x	Scalar values (e.g., $3, e, \pi,$)
θ, ϕ	Angular values (e.g., $\frac{\pi}{2}, 120\,\mathrm{deg}$)
v_x, v_y, v_z or v_1, v_2, v_3	Coordinates of 3D vector $\mathbf{v}$
$m_{1,1}, ..., m_{i,j}, ..., m_{n,m}$	Coefficients of matrix $\mathbf{M} = [m_{i,j}]_{n,m}$
$(x_1, ..., x_k)$	A k-tuple (for $k=2$, a pair; for $k=3$, a triple)
$[a, b]$	Closed real interval $\{x \mid a \leq x \leq b\}$
(a, b)	Open real interval $\{x \mid a < x < b\}$ (e.g., $(-\infty, \infty)$)
$[\![n]\!]$	Integer set $\{0, 1, ..., n\}$
$[\![n]\!]^*$	Integer set $[\![n]\!] \backslash \{0\} = \{1, ..., n\}$
$(\!(a, b]\!], [\![a, b)\!)$	Integer set closed at one end and open at the other: $(\!(a, b]\!] = \{a+1, ..., b\}, [\![a, b)\!) = \{a, ..., b-1\}$

Vectors:

$\overrightarrow{OP}$	Coordinate-free vector defined by points O and P
$\mathbf{v}$	Vector notation in some given coordinate system
$\mathbf{v}^T$	Transpose vector
$\|\|\mathbf{v}\|\|$	Magnitude of vector $\mathbf{v}$ (L_2 norm)
$d_2(\mathbf{p}, \mathbf{q})$	Distance between $\mathbf{p}$ and $\mathbf{q}$, length $\|\|\mathbf{pq}\|\|$
$\mathbf{e}_1, ..., \mathbf{e}_d$	Unit vector basis of a d-dimensional vector space (or eigenvectors)
$\mathbf{p} = \begin{bmatrix} p_x & p_y \end{bmatrix}^T$	2D Inhomogeneous vector
$\mathsf{p} = \begin{bmatrix} p_x & p_y & p_w \end{bmatrix}^T$	2D Homogeneous vector, often obtained by appending to $\mathbf{p}$ the w-coordinate set to 1 ($\mathsf{p} = [\mathbf{p}\ 1]^T$), except for ideal points ($w = 0$)
$\mathbf{s} = \begin{bmatrix} s_x & s_y & s_z \end{bmatrix}^T$	3D Inhomogeneous vector ("s" for space)
s	3D Homogeneous vector, often obtained by

	appending to $\mathbf{s}$ the w-coordinate set to 1 ($\mathbf{s} = [\mathbf{s}\ 1]^T$), except for ideal points ($w = 0$)
$\mathbf{v}^{\perp}$	Arbitrary perpendicular vector to $\mathbf{v}$ of same magnitude
$\mathbf{v}_1 \cdot \mathbf{v}_2$	Dot or inner product. (equivalent to vector multiplication $\mathbf{v}_1^T \mathbf{v}_2 = \mathbf{v}_2^T \mathbf{v}_1$; $\mathbf{v}_1 \cdot \mathbf{v}_2 = \|\|\mathbf{v}_1\|\| \ \|\|\mathbf{v}_2\|\| \cos\theta$, where θ is the angle made by vectors $\mathbf{v}_1$ and $\mathbf{v}_2$)
$\mathbf{v}_1 \times \mathbf{v}_2$	Cross product: $\|\|\mathbf{v}_1 \times \mathbf{v}_2\|\| = \|\|\mathbf{v}_1\|\| \ \|\|\mathbf{v}_2\|\| \sin\theta$

Arrays & Matrices:

$\mathbf{S}, \mathbf{I}$	1D or 2D array of elements $\mathbf{S}[k]$: the kth element of $\mathbf{S}$ $\mathbf{I}[x, y]$: the pixel of (x, y) coordinates (or $\mathbf{I}[y, x]$ depending on the indexing context)
$\mathbf{M}$	Matrix or image notation
$\mathbf{M}[y, x]$	Matrix coefficient at yth row and xth column $\mathbf{M}[y, x] = m_{y,x}$
$\mathbf{M}^T$	Transpose matrix
$\mathbf{I}$, $\mathbf{I}_d$	Identity $(d \times d)$ square matrix
$\det \mathbf{M} = \|\mathbf{M}\|$	Determinant of matrix $\mathbf{M}$ (zero if singular)
$[\mathbf{u}]_\times = \mathbf{M}$	Skew antisymmetric matrix ($\mathbf{M}^T = -\mathbf{M}$) defined as follows: $[\mathbf{u}]_\times = \begin{bmatrix} 0 & -u_z & u_y \\ u_z & 0 & -u_x \\ -u_y & u_x & 0 \end{bmatrix}$ and $\mathbf{u} \times \mathbf{v} = [\mathbf{u}]_\times \times \mathbf{v}$
$\mathrm{rank}(\mathbf{M})$	Rank of matrix $\mathbf{M}$
$\mathrm{trace}(\mathbf{M})$	Trace of matrix $\mathbf{M}$ (sum of its diagonal elements: $\sum_i m_{ii}$)
$\mathrm{adj}(\mathbf{M})$	Adjoint of matrix $\mathbf{M}$ (elements are signed cofactors)
$\mathbf{R}, \mathbf{P}, \mathbf{T}$	Inhomogeneous matrices
$\mathsf{\mathbf{R}}, \mathsf{\mathbf{P}}, \mathsf{\mathbf{T}}$	Homogeneous matrices

Quaternions:

$\hat{\mathbf{q}}$	Quaternion $\hat{\mathbf{q}} = [s\ \mathbf{v}]^T$ (unit quaternion $\hat{\mathbf{q}} = \cos\theta + \mathbf{u}\sin\theta$)
$\bar{\hat{\mathbf{q}}}$	Quaternion conjugate $\bar{\hat{\mathbf{q}}} = [s\ \ -\mathbf{v}]^T$
$\hat{\mathbf{q}}_1\hat{\mathbf{q}}_2$	Quaternion multiplication: $\hat{\mathbf{q}}_1\hat{\mathbf{q}}_2 = [s_1 s_2 - \mathbf{u_1}\mathbf{u_2} \quad \mathbf{u_1} \times \mathbf{u_2} + s_1\mathbf{v_2} + s_2\mathbf{v_1}]^T$
$\|\|\hat{\mathbf{q}}\|\|$	Quaternion norm $\sqrt{\hat{\mathbf{q}}\bar{\hat{\mathbf{q}}}} = \sqrt{s^2 + \|\|\mathbf{u}\|\|^2}$
$\hat{\mathbf{q}}^{-1}$	Quaternion inverse $\frac{\bar{\hat{\mathbf{q}}}}{\|\|\hat{\mathbf{q}}\|\|}$
$\hat{\mathbf{q}}^\lambda$	Quaternion power: $\hat{\mathbf{q}}^\lambda = (\exp(\theta\mathbf{u}))^\lambda = \cos\lambda\theta + (\sin\lambda\theta)\mathbf{u}$
$\log\hat{\mathbf{q}}$	Quaternion logarithm: $\log\hat{\mathbf{q}} = \log\exp(\theta\mathbf{u}) = \theta\mathbf{u}$

Space:

$\mathbb{R}^2, \mathbb{R}^3, \mathbb{R}^d$	2D, 3D, and dD Euclidean spaces
$\mathbb{P}^2, \mathbb{P}^3, \mathbb{P}^d$	2D, 3D, and dD projective spaces
$\mathbb{SO}^3$	Space of 3D rotations
$\mathbb{C}^2$	Space of complex numbers ($\mathbb{C}^2 = \{a + \mathbf{i}b \mid (a, b) \in \mathbb{R}^2\}$)
$\mathbb{Q}$	Set of quaternions ($\mathbb{Q} = \{a + b\mathbf{i} + c\mathbf{j} + d\mathbf{k} \mid (a, b, c, d) \in \mathbb{R}^4\}$)
$\mathbb{A}$	Affine space

Functions & Partial Derivative Operators:

$n!$	Factorial $n! = 1 \times 2 \times ... \times n$
$\binom{n}{k}$	Binomial coefficient $\frac{n!}{k!(n-k)!}$
$\vert \cdot \vert$	Absolute value
$\lfloor a \rfloor$	Floor of a (e.g., $\lfloor 2.312 \rfloor = 2$)
$\lceil a \rceil$	Ceiling of a (e.g., $\lceil 2.312 \rceil = 3$)
$\mathrm{sign}(a)$	Sign of a (e.g., $\mathrm{sign}(-3) = -1, \mathrm{sign}(5) = 1, \mathrm{sign}(0) = 0$)

Dirac function

$$\delta(x, y) = \begin{cases} 1 & \text{if and only if } x = 0 \text{ and } y = 0, \\ 0 & \text{otherwise.} \end{cases}$$

(Krönecker symbol)

$f(x_1, x_2, ..., x_k)$ — Function f of k variables $x_1, ..., x_k$

Gradient ∇f

$$\nabla f = \begin{bmatrix} \frac{\partial f}{\partial x_1} & \dots & \frac{\partial f}{\partial x_d} \end{bmatrix}^T$$

Laplacian Δf

$$\Delta f = \frac{\partial^2 f}{\partial x_1^2} + \dots + \frac{\partial^2 f}{\partial x_d^2}$$

Jacobian $\mathbf{J}f$

$$f : \mathbb{R}^d \to \mathbb{R}^n,\ \mathbf{J} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \dots & \frac{\partial f_1}{\partial x_d} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \dots & \frac{\partial f_n}{\partial x_d} \end{bmatrix}$$

Hessian $\mathbf{H}f$

$$f : \mathbb{R}^d \to \mathbb{R}^d,\ \mathbf{H} = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \dots & \frac{\partial^2 f}{\partial x_1 \partial x_d} \\ \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_d \partial x_1} & \dots & \frac{\partial^2 f}{\partial x_d^2} \end{bmatrix}$$

($\mathbf{H}f = \mathbf{J}\nabla f$)

Geometric entities:

P	Point P
S	Line segment S
O	Object O
H	Plane H
$H : \mathbf{n}^T\mathbf{v} = 0$	Plane H defined by homogeneous equation: $n_1v_1 + n_2v_2 + n_3v_3 + n_4v_4 = 0$
$\mathrm{Ball}(B, r)$	Ball of circumcenter B and radius r
$\triangle PQR$	Triangle with vertices P, Q, and R
$\mathcal{S} = \{S_1, ..., S_n\}$	Set of objects
$\mathrm{aff}(\mathcal{S})/\mathrm{conv}(\mathcal{S})$	Affine/convex space defined by set $\mathcal{S}$

Probabilities, Statistics, and Inequalites:

$\mathbf{Pr}[\mathrm{Event}]$	Probability of event Event
$\hat{S}$	Random variable
$\mathbf{E}(\hat{S})$	Expectation of random variable $\hat{S}$
$\mathbf{Var}(\hat{S})$	Variance of random variable $\hat{S}$
$\sigma(\hat{S})$	Standard deviation of random variable $\hat{S}$ $(\sigma(\hat{S}) = \sqrt{\mathbf{Var}(\hat{S})})$
$\hat{X}_E = I(E)$	Indicator random variable of event E
$\mathbf{Pr}[\hat{S} \geq c] \leq \frac{\mathbf{E}(\hat{S})}{c}$	Markov inequality (non-negative discrete random variable)

Data Structures:

Q	Data structure Q (e.g., a queue)
S.procedure()	Call function procedure without argument on S
S.procedure($\mathcal{P}$)	Call function procedure with argument $\mathcal{P}$ on S
$\mathsf{P} \leftarrow \emptyset$	Initialize an empty data structure P

Asymptotic Complexity:

$O(f)$	Upper bound
$\Omega(f)$	Lower bound
$\Theta(f)$	Optimal bound
$o(f)$	Nonasymptotically tight upper bound
$\tilde{O}(f)$	Expected running time of randomized algorithms
$\bar{O}()$	Average running time of deterministic algorithms

Radiometric Quantities and Units:

Radiance	$\frac{W}{sr.m^2}$	Watt per steradian per meter square
Luminance	$\frac{cd}{m^2}$	Candela per meter square
Irradiance	$\frac{W}{m}$	Watt per meter
Illuminance	lx	Lux

In this book, we either present algorithms in C++-style language or at a higher-level pseudocode abstraction style. The argmin and argmax notations are often used in those algorithms. In practice, in a C++-style, we often compute both the min and argmin, or max and argmax. Let us consider a d-dimensional vector $\mathbf{v}$. We mathematically write the maximum of its coordinate as $m = \max_{i=1}^{d} v_i$. The maximum coordinate is obtained from the kth principal axis, with $k = \mathrm{argmax}_{i=1}^{d} v_i$. Thus, we have the following max/argmax relationship: $v_{\mathrm{argmax}} = \max$.

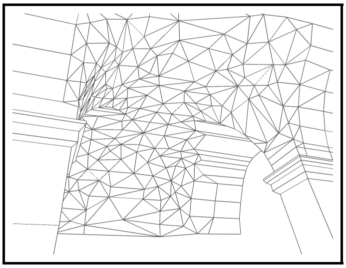
Here is the C++ code for performing those max and argmax operations:

```
class vector{ public:
                int d;  double *x;
                // create a random vector
                vector(int dim) { d=dim;  x=new double[d];
                                for(int i=0;i<d;i++)
                                   {x[i]=rand()/(double)RAND_MAX;}
                              }

                // delete a vector  ~vector() {delete [] x;}
                // maximum coordinate value
                double max()  { double value=x[0];
                                for(int i=1;i<d;i++)
                                  if (x[i]>value) value=x[i];
                                  return value; }

              // coordinate axis that has
              // maximum value
              int argmax()  { int axis=0;
                              for(int i=1;i<d;i++)
                                  if (x[i]>x[axis]) axis=i;
                              return axis;  }
              };
```

Colophon

This book has been typeset using LaTeX system on Microsoft® Windows® operating system. A special LaTeX class has been written to fit the typesetting rules of Charles River Media. Most of the figures have been prepared with the `Ipe` extensible drawing editor environment of Professor Otfried Cheong (available online at *http://ipe.compgeom.org/*). The book project has been managed using the excellent TeXnicCenter tool (*http://www.toolscenter.org/*) that provides a visual integrated environment for editing and compiling a full LaTeX book project made of many LaTeX files. I used `XnView` image browsing software (*http://www.xnview.com/*) to capture screenshots and extract frames from movies. `XnView` was also instrumental for the various image conversions I needed (`bmp`, `png`, `eps`, etc.). The Internet was a much appreciable resource for finding related materials and references. I can hardly imagine how I could have typeset this book without this Web information. I used the ACM (*http://portal.acm.org/*) and IEEE (*http://www.computer.org/publications/dlib/*) digital libraries for retrieving original papers, and sometimes their `BibTeX` labels.

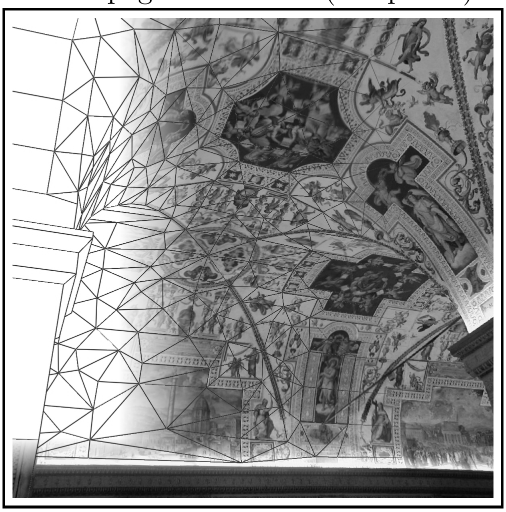
The cover page image was created by compositing images of a photogrammetric set of a 3D reconstruction of the Vatican library (no religious meaning):


3D Mesh


Textured Mesh


Photograph

Cover page illustration (composite):

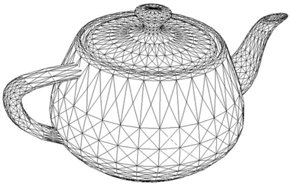


Those images are courtesy of © Stéphane Nullans (France). Used with permission.

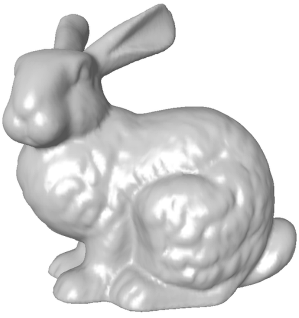
There is quite a lot of famous data in visual computing that is constantly used as a test bed for evaluating and comparing algorithms. We succinctly present the hall of fame on the next page.

HALL OF FAME

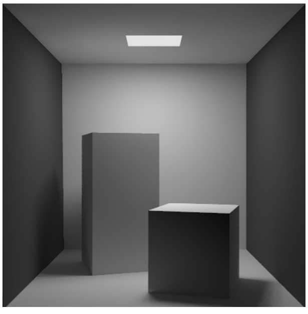
The 512 × 512 24-bit `lena` picture and narrative story on how it became a de facto test image in the image processing and computer vision communities can be read online at *http://www.lenna.org*
Warning: the full picture contains nudity.



The Utah 3D teapot has traditionally been used in computer graphics. There is even a function named `glutWireTeapot` in the `glut` API to draw it. The Utah teapot history, including the descriptions of the original one that differs from the `glut` version, is summarized online, at *http://sjbaker.org/teapot/*.



The 3D `bunny` model of the computer graphics laboratory of Stanford's university is often used for testing mesh algorithms. The 69,451-triangle `bunny` was acquired from a real-world model in 1993. The `bunny` history can be enjoyed online at either *http://graphics.stanford.edu/data/3Dscanrep/*, or *http://www.gvu.gatech.edu/people/faculty/greg.turk/bunny/bunny.html*.



The Cornell box is a traditional data set used for computing radiosity or simulating global illumination algorithms in computer graphics. The Cornell box history, data set, and experiments (including comparisons with the measured real-word box) are further described online at *http://www.graphics.cornell.edu/online/box/*. PovRay (*http://povray.org*) provides a script file `cornell.pov` to render your own radiosity box image.

Main Conferences and Publications in Visual Computing:

(List is nonexhaustive)

Main conferences:

- Annual Conf. Comp. Graphics and Interactive Techniques, ACM SIGGRAPH
- Annual Conference on Human Factors in Computing Systems, ACM CHI
- Biannual Symposium on Interactive 3D Graphics and Games, ACM I3D
- Annual Conference on Vision and Pattern Recognition, IEEE CVPR
- Annual International Conference on Computer Vision, IEEE ICCV
- Biannual European Conference on Computer Vision, IEEE ECCV
- Biannual Conference on Pattern Recognition, IAPR ICPR
- Annual Computer Graphics International, CGS CGI
- Annual Eurographics, European Association for Computer Graphics
- Annual International Conference on 3D Web Technology, ACM WEB3D
- Annual Conference on Point-Based Graphics, IEEE/Eurographics
- Annual Symposium on Geometry Processing, Eurographics SGP
- Annual Canadian Conference on Graphics Interface, GI
- Annual Symposium on Computational Geometry, ACM SoCG
- Annual Symposium on Solid and Physical Modeling, ACM SPM
- Annual Symposium on Information Visualization, IEEE IV
- Annual Canadian Conference on Computational Geometry, CCCG
- Annual Conference on Smart Graphics, SG
- Annual Game Developers Conference, GDC
- Annual Pacific Conference on Computer Graphics and Applications, PG
- Annual Conference on Voronoi Diagrams in Science and Engineering, VD

Main journal publications:

- Transactions on Computer Graphics, ACM TOG
- Transactions on Pattern Analysis and Machine Intelligence, IEEE TPAMI
- Transactions on Visualization and Computer Graphics, IEEE TVCG
- Discrete & Computational Geometry, Springer-Verlag DCG
- The Visual Computer, Springer-Verlag VCJ
- Computational Geometry: Theory and Its Applications, Elsevier CGTA
- Transactions on Applied Perception, ACM TAP
- Graphical Models and Image Processing, Elsevier GMIP
- Computer Graphics and Applications, IEEE CGA

Major tradeshows:

• Annual International Conference on Computer Graphics and Interactive Techniques, SIGGRAPH
• Annual Electronic Entertainment Expo, E3
• Annual Game Development Conference, GDC
• Annual National Association of Broadcasters, NAB

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