A Knowledge Base for the Emerging Discipline of Computer Graphics: Report of the SIGGRAPH Education Committee Curriculum Working Group

Cary Laxer[1] and Jenny Orr[2]
[1]Rose-Hulman Institute of Technology, Terre Haute, Indiana, U.S.A.
[2]Willamette University, Salem, Oregon, U.S.A.

The Emerging Discipline of Computer Graphics

The idea of a discipline, or knowledge domain, is based upon three essential characteristics [Bertoline 1998, Rumble 1998, Sheth & Parvatiyar 2002]. First, theoretical and conceptual specialization must be demonstrated, often through a well-established and fairly unique research agenda. Next, it must be shown that the discipline can be characterized by a unique cultural identity. Finally, a discipline must demonstrate relative autonomy, in that a distinctive knowledge base can be articulated. That computer graphics has emerged as a discipline should be evident from today's professional organizations such as SIGGRAPH and Eurographics that promote research and communication in the field.

For the past several years, the SIGGRAPH Education Committee has sponsored a Curriculum Working Group, whose task has been to define the knowledge base associated with the computer graphics discipline. Because this knowledge base is most closely associated with the broader discipline, and not any particular application or industry, it has great potential as a starting point for curriculum development and assessment. It defines, in broad terms, those skills and concepts that every computer graphics student should have some exposure to and with which every instructor ought to have some familiarity.

Previous Work

The ACM SIGGRAPH Education Committee has sponsored a number of educational resource projects and reports that list topics and curricula for computer graphics education. Perhaps the most significant of these was the "Computer Graphics Taxonomy Project" by Jacquelyn Ford Morie. The report aims to define a taxonomy of CG concepts that covers all topics relevant to computer graphics. "The taxonomy includes basic and advanced CG concepts that are pertinent across many disciplines, from art to engineering" [Morie 2001]. The SIGGRAPH Education Committee has sponsored other curriculum projects, but each was focused on a single sub-discipline of CG, e.g., art, scientific visualization, computer science, and engineering.

History of the Curriculum Working Group

The SIGGRAPH Curriculum Working Group can trace its beginnings to the SIGGRAPH 2001 Conference Educators Program. One of that year's forums was titled "The Emerging Computer Graphics Discipline," led by Gary Bertoline of Purdue University [Bertoline 2001]. Bertoline challenged the audience to think of computer graphics as a renaissance discipline, on a continuum between art and computer science and electrical and computer engineering.

Discussions led to a second forum at the SIGGRAPH 2002 Conference, where the goal was to try to develop a knowledge base for the discipline of computer graphics. Bertoline and Laxer suggested that computer graphics had a multidisciplinary nature, involving components of cognitive psychology, geometry, imaging science, technology, art and design, and computer science. The audience was challenged to come up with core topics that were crucial to a computer graphics student's education and that addressed this multidisciplinary nature. Two long lists of topics were generated, one from the computer science perspective and one from the art perspective. From these lists, a knowledge base for the computer graphics discipline began to emerge.

The next step was to devote significant effort to refining this knowledge base and the creation of a broad curricular framework for computer graphics. To that end, Bertoline and Laxer submitted a grant proposal to the SIGGRAPH Education Committee to bring ten computer graphics educators, representing computer science and art, together for a one day workshop immediately preceding the SIGGRAPH 2003 conference. At that workshop, the participants agreed on a common core set of topics for all computer graphics students. Further, tracks for the artistically inclined student and the technically inclined student were identified.

At the conclusion of the 2003 workshop, the participants realized that they had significant input from the computer graphics education community, but no input from the computer graphics industry, the very people who would employ graduates of computer graphics programs. Thus, the working group decided to hold another workshop the day before the SIGGRAPH 2004 conference and invite industry representatives to meet with the group and express their thoughts on what skills and knowledge they would like to see in students graduating from computer graphics programs. Excellent input was received from several industry representatives which the working group used to refine the developing curriculum.

In 2005 the working group met once more on the day before the SIGGRAPH conference to finalize the core set of topics and further refine the two tracks (artistic and technical). Excellent progress was made, and momentum was built, but the work could not be accomplished in the one day. The group decided to meet again that November to continue the work.

Finally, in 2006, another open forum was held at the SIGGRAPH conference to receive broader feedback on the proposed knowledge base. Audience input affirmed that the working group's efforts were in the right direction. The working group met following the SIGGRAPH conference to refine the knowledge base one last time, with input from international colleagues (representing Europe, South America, and Japan) adding to the discussion.

Proposed Curriculum/Knowledge Base

What follows is the knowledge base as defined during the Working Group's August 2006 meeting. Of interest, the two tracks defined during the earlier meetings were merged into a single knowledge base. The group's rationale was that this ought to reflect a united knowledge base defining the *discipline* of computer graphics, rather than a knowledge base for a collection of separate but overlapping sub-disciplines. That is, it is suggested that every computer graphics student will invest some amount of time, whether small or large, with every listed concept. This approach was reaffirmed by the comments made at the SIGGRAPH 2006 Educators Forum session where this knowledge base was presented.

There are seventeen broad headings, many with sub-headings and additional detail. Content isn't meant to be exhaustive but, instead, provide general guidance and examples of curricular experiences and concepts.

Fundamentals – an overview of the field; foundational concepts; industry highlights; careers; roles and responsibilities; milestones in the chronology of CG; CG as a contributor to other fields and disciplines; CG as a discipline in its own right. CG production cycle: stages, tasks, and products. Overview of:

- Vocabulary – meaningful terms and concepts; broadly-based theoretical frames and issues that are essential to an understanding of the field (art, design, computer graphics, and other sub-areas)
- Hardware – computers; monitors and displays; networks; digital media; platform technologies; architectures
- Software Systems – programs/applications; operating systems; structures; formats for data storage
- Representations of Visual Systems – pixels and polygons; 2D and 3D display, color
- Foundational/introductory art skills and concepts

Professional Issues

- Team work
  - Project management
    - Planning: stages, time, resources
    - Evaluation
  - Collaboration issues and group dynamics
    - Roles of team members
    - Time management
- Ethical Issues
  - Professional codes of ethics and good practice
  - Case studies in ethics
- Intellectual Property
  - Meaning and examples of "intellectual property"
    - Including "stealing" versus buying
  - Copyright
  - Licensing
  - Fair use
- Accessibility
  - Accommodating disabilities

        - Motor disabilities
        - Visual disabilities
        - Auditory disabilities
        - Color blindness
    - Availability and access to information
- Business Issues
    - Business planning
        - Product research
        - Market analysis
        - Cost analysis
    - Compensation
- Portfolio development/presentations

Physical Sciences
- Mechanics
    - Collision detection
    - Movement in the real world
    - Newton's laws of motion; weight, mass, and inertia
- Light - color, refraction, reflection, dispersion, fluorescence
- Natural phenomena
    - Fluid dynamics – fire, smoke, water, clouds, turbulence
    - Biological systems – plant morphological

Math
- Coordinate systems
    - Local coordinate systems vs. world coordinate systems
    - Cartesian, polar, spherical
    - 2D and 3D coordinate systems
    - Homogenous
- Transformations
    - Viewing – perspective, orthographic
    - Rotation, translation, scaling
    - Deformations
- Random Numbers
- Geometry – plane and solid geometry; points, lines, planes, and space; angles
- Matrix and vector algebra
- Complex numbers and quaternions
- Parametric/non-parametric representations
- Numerical methods

Perception & Cognition
- Visual
- Spatial
- Motion
- Interactive environments
- Psychology
- Human factors

Human Computer Interaction (HCI)

Programming & Scripting
- Concepts
    - Variables, arrays, loops, functions, recursion
    - Software design and debugging
    - Object-oriented programming;
- Languages
    - High Level - Java, C++, Python
    - Scripting – MEL, JavaScript
- Shading Languages – Renderman, Cg, OpenGL SL, HLSL
- Graphics API – OpenGL, DirectX, Java3D
- Data Structures – lists, stacks, queues, trees, graphs, libraries
- Algorithms – sorting, searching

Animation
- Basics
    - Time and motion
        - Interpolation
        - Morphing
    - Modeling
        - Rigging
            - Forward kinematics
            - Inverse kinematics
        - Texture
        - Lighting
        - Rendering
    - Character
    - Cinematography
- Motion control and capture
- Rigid body dynamics
- Procedural animation
- Particle dynamics

Rendering
- Scanline rendering
- Global illumination
    - Radiosity
    - Ray tracing
- Algorithms
    - Primitives – lines, polygons
    - Hidden surface removal
    - Clipping
    - Culling
- Shading
    - Lighting models

  - Material properties – reflection, refraction, and shading models
  - Texture mapping
  - Procedural shading
- Anti-aliasing
- Camera models – depth of field, shutter, motion blur, resolution, safe areas, projection types
- Tone reproduction – color management, HDR, perceptual tone mapping

Modeling
- 3D modeling
  - Polygonal modeling
  - Parametric primitives
  - NURBS
  - Lathed and extruded objects
  - Subdivision surfaces
  - Level of detail
  - Normals
  - Hierarchical
- Character design
  - Physical attributes
  - Designing for animation
- Architectural design

Graphics Hardware
- Output devices
- Input devices
- Special purpose chip sets/graphics cards
- Comparison of graphics card features
- Storage solutions
- Networking
- Virtual/augmented reality

Digital Images
- Image Processing
  - Filtering – Fourier analysis, wavelets, convolution
  - Sampling/quantization issues
  - Noise
  - Enhancement – edge detection, sharpening
- Image compression
  - encoding, decoding
  - color reduction techniques
- Graphics/Image file formats
  - Vector vs. raster representations
  - Standard formats - e.g., JPEG, CGM, TIFF, PNG, GIF, RAW
- Digital Cameras – sensors
- HDRI
- Computer vision
  - image acquisition
  - image segmentation
  - image understanding

Communications
- Writing
  - Technical
  - Creative
    - Storyboarding
    - Character development
    - Scriptwriting
  - Professional
- Oral
  - Improvisation
  - Speech & presentations

Cultural Perspectives
- Genres
- Socioeconomic effects
- Global aspects
- Age and gender

Art and Design Foundation
- Theory
  - Fundamentals of art and design,
  - Aesthetics, visual language
  - Color theory
  - Composition, layout, symmetry and asymmetry, chaos theory and fractals
- History of art and design, computer graphics, special effects, and new media
- Two dimensional expression - painting and drawing
- Three dimensional expression - handmade and computer aided sculpture and three-dimensional modeling; three-dimensional structures, both symmetrical and asymmetrical.
- Overview of theoretical, practical, and historical aspects of:
  - Animation
  - Film and video
  - Game design
  - Graphic design and scientific illustration
  - Haptics
  - Sound and audio
  - Web design
- Creativity and Ideation
- Impact – Media as a social, cultural, and political force.

Real-time Graphics

- Requirements
  - Visual realism for RTS (real-time systems)
  - HCI for RTS
  - Optimization of performance and visual realism
- Hardware
  - CPU and GPU (graphics processing unit)
  - Networking for RTS
  - Algorithms
    - Rendering pipeline (hardware)
  - Data structures
    - Buffers: color, depth, texture, accumulation, stencil
- Software
  - Algorithms
    - Rendering pipeline (software)
    - Level-of-detail: discrete and continuous model definition, runtime management
    - Collision detection
  - Data structures
    - Texture maps, mipmaps
    - Light maps
    - Space partitioning: binary space partition (BSP), quadtree and octtree
- Applications
  - Gaming and simulation
  - VR and AR

Advanced Topics

- Data/scientific visualization
- Artificial intelligence
- Calculus and differential equations
- Dynamical systems

We hope that the above knowledge base can be used as a starting point in the CGE06 workshop discussion. The purpose of the workshop is to define an international curriculum in computer graphics with respect to the European Union Bologna requirements, while the purpose of the above knowledge base is to serve as a basis for developing an interdisciplinary curriculum in computer graphics that is appropriate, but not limited to, the United States. The two goals, while not identical, have significant overlap. The EU curriculum, which is to be built out of a computer science curriculum, will naturally contain most portions of the knowledge base concerned with programming, mathematics, and some science. The primary difference is the significant weight given to art and design in the US curriculum. While the EU degree will be more focused on the science and technology of computer graphics, the authors feel that some exposure to art and design, even if limited, is valuable. After all, the ultimate goal of computer graphics is to create images, and so it benefits every student of computer graphics to have 1) some understanding of what makes for effective images and 2) experience in how the tools are used. This understanding can motivate the direction of future research and application development.

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