COMPUTER GRAPHICS LABORATORY
Department of Computer Science
University of Waterloo
Fall 1981 Review

John C. Beatty

Kellogg S. Booth

Introduction

This document reviews the status of teaching, research, and development activities within the Computer Graphics Laboratory of the Department of Computer Science at the University of Waterloo. It is intended to serve a number of purposes:

- coordinating activity within the group, so as to minimize duplicated effort and maximize the utility and lifetime of each person's work.

- informing the wider university community, whether they are students looking for an interesting master's topic, or a faculty member with an application in mind which could benefit from the use of our facilities.

- informing industry. We already have close ties with Electrohome, NRC and MPS Associates, and are exploring the possibilities of cooperation with several other companies. A clear statement of our activities and resources will facilitate the development of other such relationships.

- clarifying future hardware and software needs by providing a definite plan of action for the next two years.

Teaching

We presently offer two classes in computer graphics at the University of Waterloo. The first (CS 488/688) is an introductory class which has been taught to fourth year undergraduates and graduate students for about four years now. Although it is one of the more demanding fourth year courses offered by the Department of Computer Science, it is also one of the more popular, having an enrollment of approximately 20 students each term.

The second (CS 788) is an advanced course in computer graphics, taught once each year. It covers selected research topics in depth.

The Introductory Graphics Class.

The aim of this course is to give students a "complete" overview of computer graphics. We cover basic hardware, software and human factors, discuss current trends in computer graphics, and briefly survey some of the flashier research presently being done in visible surface processing and antialiasing. Students read a number of published papers as well as the text (Principles of Interactive Computer Graphics by Newman and Sproull).

We believe in "learning by doing," so each student implements (in Pascal) a graphics package which supports a linked list data structure for describing images, perspective and orthographic projections from an arbitrary eyepoint, scaling, rotation, translation, windowing, three forms of text, clipping, viewporting, and a simple z buffer visible line algorithm. The package is highly modular and device independent. Students write about 4,500 lines of code and implement four device drivers. The work is spread over nine assignments, which are handed out at the beginning of the term so that students may plan ahead. In the last assignment students are asked to do something - anything! - with their package. Two of the more interesting pictures which have resulted appear on the next page.

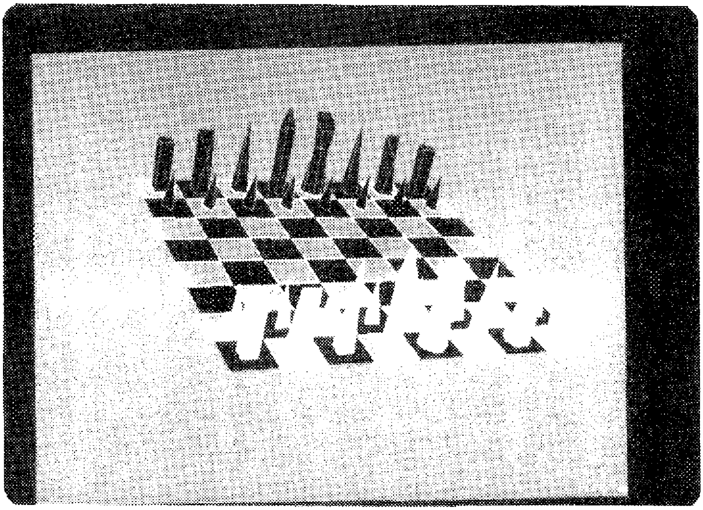
Although we are teaching graphics, not software engineering, students taking the course often report that the chance to write a software system of this size is a valuable experience. The package has also served as a starting point for various research projects, several of which are discussed in subsequent sections of this report.

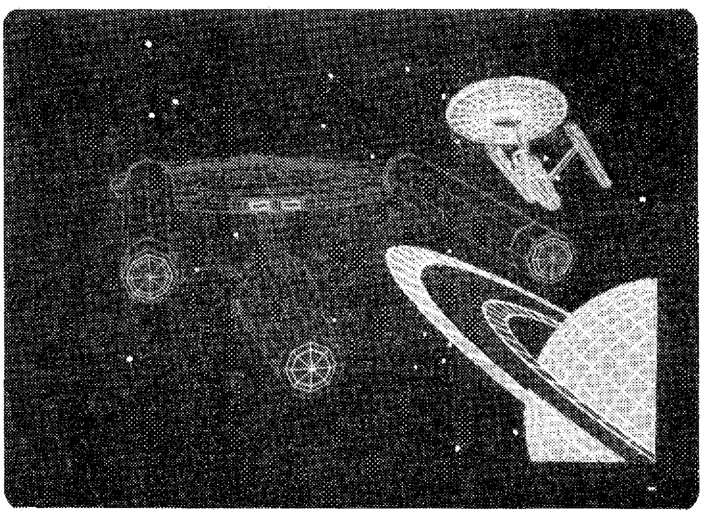
A more detailed discussion of the introductory graphics course appeared in [5].

Future Plans for CS 488/688.

In the past the graphics class has made use of the Math Faculty Computing Facility (MFCF) Honeywell 66/60, a vastly overloaded machine. For graphics output students generally have used Hewlett-Packard 2648A terminals and a Varian electrostatic plotter. This term the course is being taught on the DEC VAX 11/780 recently purchased by the Mathematics Faculty. This will entail some changes in the way in which source code for the graphics package is structured, but we are staying with Pascal. Students should find the VAX/Unix environment superior to the Honeywell.

Equally exciting is the imminent arrival of six Electrohome Telidon terminals which are being donated to the Laboratory by Electrohome, Ltd. These will be connected to the VAX, and





several will be equipped with graphics tablets purchased by the University. As we already have a device driver for Telidon/pdi terminals we expect to integrate these displays into the graphics course immediately.

Use of these terminals will enable students to experiment readily with color and with visible surface and shading algorithms. The availability of tablets will enable us to concentrate more heavily on graphics input than has been possible in the past. We would like to obtain a low cost color ink jet or matrix printer so that students can economically obtain hardcopy of images they produce on a Telidon display.

We expect to cooperate with Electrohome in developing enhanced firmware supporting highly interactive local service in their Telidon terminal. Such firmware will enable students to gain first hand experience with interactive raster hardware. Cooperation with Electrohome should be quite close as Joe Buccino, who directs their software development effort, is a former Waterloo student who expects to begin part-time PhD work this Fall.

A good deal of our instructional material consists of 35mm slides, 16mm films, and 3/4" video tapes. To facilitate their use in the class room the University has kindly purchased video tape recording and playback units; we hope to arrange for this equipment to be permanently available in a dedicated classroom to avoid the chronic difficulties of transporting, setting up, and taking down such equipment for each lecture.

The principal deficiency in our teaching facilities remains our lack of refresh calligraphic displays. We would like to obtain 2-4 low cost line-drawing displays so that students can gain first hand experience with this area of computer graphics, and an appreciation for the relative capabilities and uses of raster vs. line drawing equipment and of passive vs. interactive hardware.

The Advanced Computer Graphics Class.

Although the course content varies from year to year, we presently emphasize geometric modelling using non-polygonal patches (typically Bezier and B-spline), high performance hardware (especially parallel hardware for raster display), antialiasing algorithms, and interaction techniques. Students read extensively from the research literature and are expected to analyse research problems - often with the goal of finding a master's or PhD thesis topic. A modest programming project or term essay is expected.

The introductory graphics class is an absolute pre-requisite for the advanced class, partly because we assume the material covered there as background, and partly because it is often convenient to cast a 788 term project as an addition to the basic package.

The pictures on the next page,are examples of such projects. To produce these pictures students added B-spline and Bezier curve/surface capability to the standard package. The B-spline image was displayed by tracing out lines of constant parameter value; the Bezier surface was displayed by recursively subdividing each Bezier surface patch (of which there are eight) until the resulting sub-patches satisified a flatness criterion, after which they were rendered as polygons. The subdivision technique is also well suited for a raster (solid area) display.

CS 788 students who elect to do a programming project are able to make use of the research equipment described in the next section in addition to the equipment which is available to students in CS 488/688.

Research

Faculty interests in computer graphics emphasize documentation graphics, visible surface algorithms and their complexity, geometric modeling, and interaction techniques. Four faculty members (Richard Bartels, John Beatty, Kellogg Booth and Jane Gentleman) and approximately fifteen graduate students are active in the laboratory, meeting every two weeks to discuss and coordinate current work and concerns. A newsletter is published before each meeting, containing minutes of the previous gathering, an agenda for the next, and information of general interest. The Laboratory regularly sponsors seminars at which members or visitors talk about their research.

Students interested in pursuing a Master's essay or thesis in computer graphics may wish to examine the file

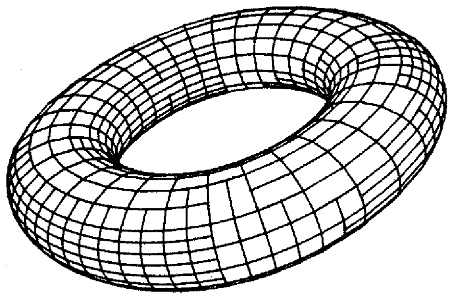
jcbeatty/projects/list

which contains a list of suggested topics, before talking to a faculty member.

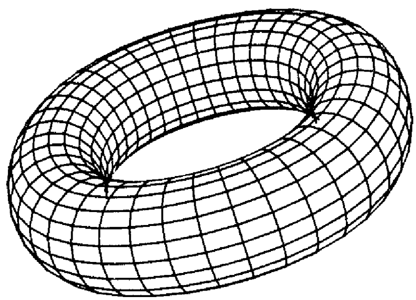
Facilities.

The Graphics Laboratory occupies about 400 square feet of space on the 4th floor of the Math and Computing Building near the Software Portability Group, with which there are a number of common interests. We expect to acquire an additional 200 square feet in the near future. The Laboratory has dedicated use of a DEC PDP 11/45 running Unix and shared access to a Honeywell Level 6 running Thoth. Terminal lines from the Lab provide access to the Honeywell 66/60 and to the VAX 11/780.

An Ikonas 2000 Raster Graphics Display is accessible from either the 11/45 or the Level 6. The Ikonas consists of a 512 by 512 by 24 bit frame buffer (which can also be configured for a 1024 by 1024 by 6 bit display), 4 color maps, a 24 by 24 programmable cross bar switch for routing image memory to the



Eight Bezier patches, rendered by subdivision.



A single B-spline patch, rendered by tracing out curves of constant parameter value.

color maps, a 200 nanosecond bit-slice microprocessor, and an Aydin/Mitsubishi color monitor. This is state-of-the-art hardware suitable for displaying high quality shaded images in color; computation intensive algorithms can be placed in the microprocessor to reduce display and interaction time. Much of the work discussed subsequently is being done on the Ikonas.

We hope to complement the Ikonas by purchasing an Evans & Sutherland Multi-Picture System, for which a grant proposal has been submitted to NSERC. The Math Faculty has agreed to contribute $50,000 in matching funds if the grant is approved. The Picture System is a high performance refresh calligraphic display able to support the scaling, rotation, translation and perspective projection of complex wire-frame images in real-time.

The Laboratory is also equipped with a Dunn 631 color camera for capturing images on 35mm film or 8x10 Polaroid film, a Tektronix 4027 color terminal (on loan from Morven Gentleman), two Electrohome Telidon terminals, a Tektronix 4014 (presently out on loan) and several Volker Craig 404's.

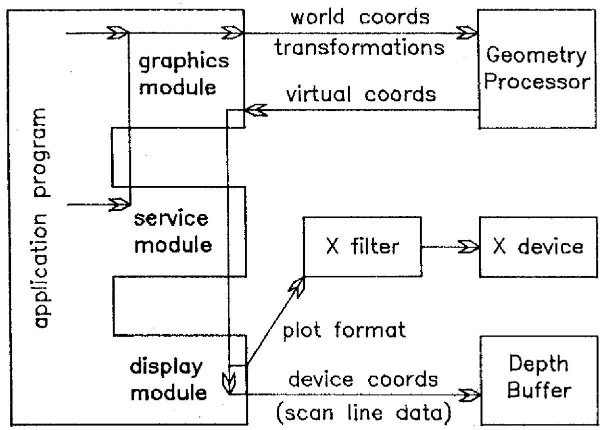
Past, present and future uses of this hardware are discussed below in conjunction with the various projects of which they are a part.

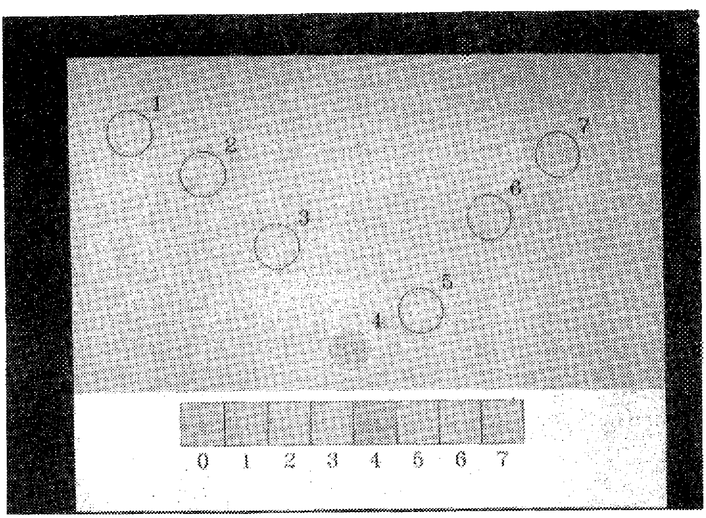
Documentation Graphics / Telidon.

The goal of this research is to develop tools for illustrating digitally typeset documents, and to apply these tools to the creation of Telidon databases.

There are a variety of sources from which graphic images may be obtained: digitized photographs; the graphical output from application programs; graphics languages; and interactive software systems for picture manipulation. In all cases the images concerned must be positioned, sized, cropped and merged into holes provided by text layout software. A dual objective is to facilitate the use of such images in the viewgraphs and 35mm slides needed for technical presentations. Often one illustration can serve usefully in both contexts.

We have designed and implemented an illustration language called Pic [1,15], an extension of work reported in [2,7], which is presently used to produce 35mm color slides. Two Pic images appear on the next page. The Pic compiler is a pre-pass for the Unix C compiler, so that all of the facilities of a regular programming language are available in addition to the graphics primitives added by Pic. One of our number (Rick Beach) is implementing a mechanism by which Pic images, and pictures generated by the CS 488 graphics package, can be directly incorporated into documents and typeset on an Autologic APS-5. This will also work on the APS Micro 5 being purchased by the University.


application program
graphics module
service module
display module
world coords
transformations
virtual coords
Geometry Processor
X filter
X device
plot format
device coords
(scan line data)
Depth Buffer


1
2
3
4
5
6
7
0 1 2 3 4 5 6 7

Future work in this area will lean more towards interactive graphics software and away from the programming language approach, making use of the potential inherent in the Ikonas raster system and the Evans & Sutherland calligraphic system. There are several aspects to this work.

Our initial effort, accomplished by Eugene Fiume, was to implement a basic painting system on the Ikonas. This software enables the user to "draw" on a color CRT, using a tablet and stylus, much as an artist paints on canvas. Two examples of Paint-ed images appear on the next page. This software is very nice for producing certain kinds of illustrations, but because the images it produces are devoid of structure (being represented simply as a 512 by 512 array of colored dots), Paint images are ill-suited for Telidon style databases or for digital typesetting. Hence current work on this software, being carried out by Darlene Plebon, will augment basic Paint capabilities by maintaining an internal, structured representation of the image being displayed. This will involve allowing the user to select, display, create, group and manipulate various graphic primitives, optionally making using of grid constraints.

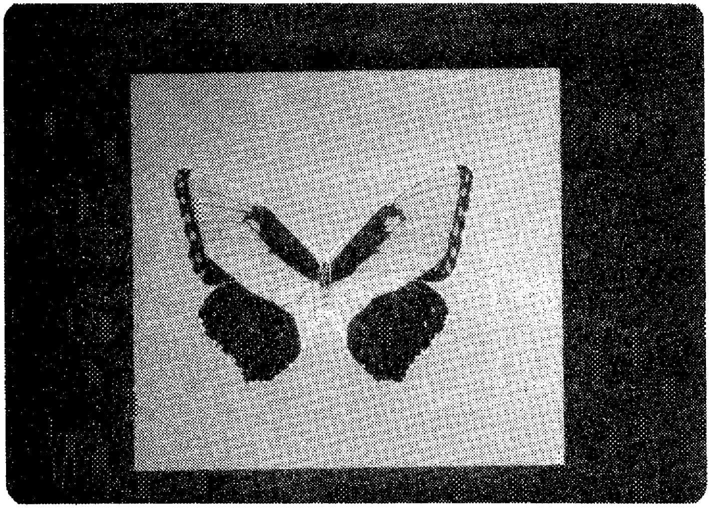
This work is being pursued jointly with the Software Portability Group. We expect to transport much of our code to the workstations they are developing, and to apply what we have learned about interaction techniques for picture manipulation to documentation graphics in a workstation environment.

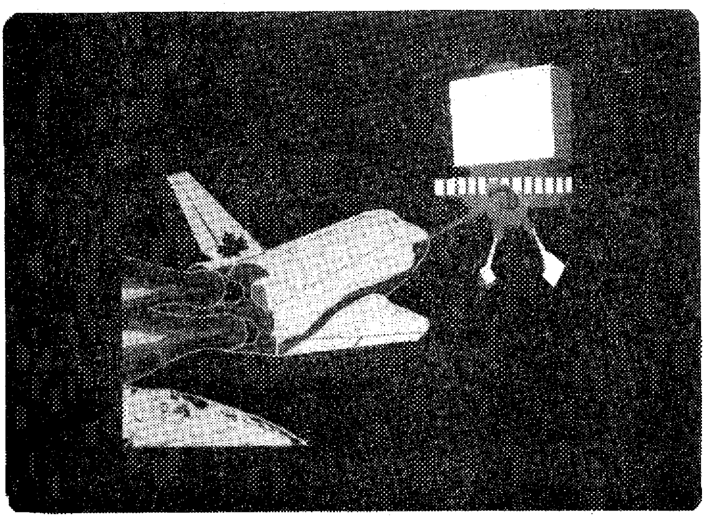
Since we wish to preserve the ability to sketch images freehand, we will also develop techniques for approximating freehand curves and boundaries with various spline approximations. This approach has the advantage of preserving the naturalness of freehand input while allowing the user to readily modify pieces of the image, to some extent obviating the need for manual dexterity in the user. If the Evans and Sutherland equipment becomes available we will explore the usefulness of a flexible hybrid system in which one can readily move back and forth between the E&S equipment and the Ikonas, utilizing the hardware transformation capabilities and speed of the first for highly interactive layout, and the color capabilities of the second to produce higher quality shaded output.

This work is being pursued in conjunction with Electrohome, which is greatly interested in using such techniques in Telidon information provider systems.

Colour Table Animation.

It takes a while to change the contents of a raster display in which the picture is represented as a 512 by 512 array of color dots or pixels - there are 256,000 dots to modify! Hence computing pictures fast enough to achieve the illusion of motion, which requires approximately 30 frames each second, is rather difficult. An alternative technique is to pre-compute a sequence of





images, store them all simultaneously in the display memory of a raster device, and modify the scroll, pan and colour table registers of the display every 1/30 of a second in order to step through them rapidly, thus achieving the illusion of motion. This technique is, of course, applicable only if one has sufficient memory as well as the pertinent registers. Often it is sufficient and satisfactory to halve the resolution so as to effectively quadruple the number of frames which can be simultaneously stored.

Steve MacKay is developing software for such colour table animation techniques. Although the present generation of Telidon terminals do not have any of the necessary hardware, we understand from Norpak that the next generation likely will. Since even very simple animation sequences can be much more effective in communicating information than static images, we are looking forward to the availability of such equipment in the Telidon environment.

A sequence of images which Steve has animated on our Ikonas using these techniques appears on the next page.

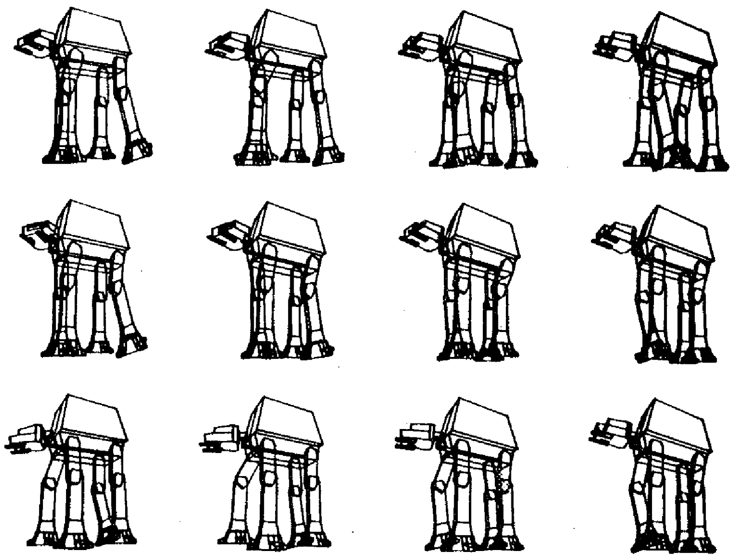
Visible Line and Surface Algorithms.

One of the more interesting and most active areas of computer graphics at present is the display of three dimensional scenes in which only the visible lines or surfaces are displayed. Activity has typically focused on techniques for the computation of such images, for improving their smoothness by building objects from curved, cubic pieces instead of polygonal mosaics, and for enhancing their realism by developing sophisticated shading and texturing techniques.

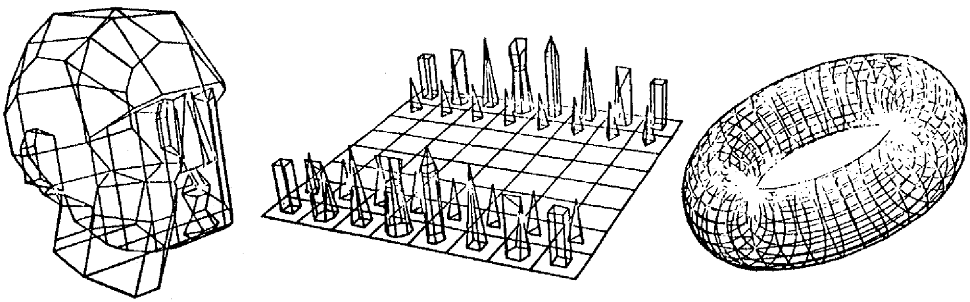
Work at Waterloo by Larry Matthies [6,*(zo], a masters student, has focused on analysing the complexity of scan line visible line and surface algorithms, on techniques by which the average and/or the worst case performance of such algorithms can be improved, and on ways in which scan line methods can be applied to problems other than visible surface computation (such as cross-hatching and VLSI layout).

Images produced with software developed in the course of this research appear on the next page. Among other things, they illustrate the use of Watkin's algorithm (whose complexity we are analysing) to perform hidden line elimination, and of a plane-sweep algorithm to perform haloing (in which the rearmost of two intersecting lines is interrupted to indicate relative depth).

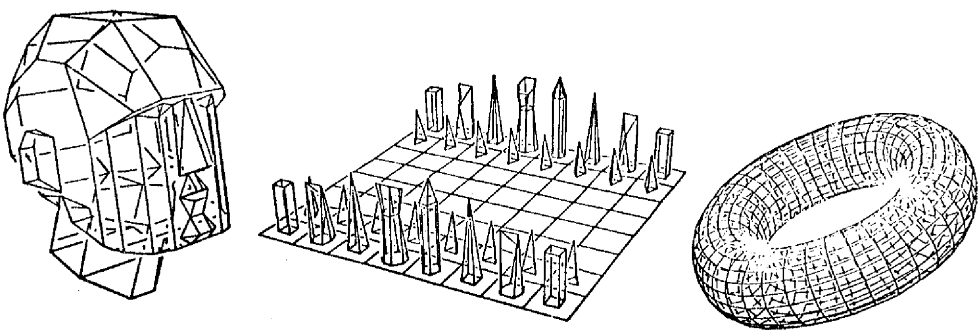
In the future we will be focusing also on the use of such algorithms in particular applications. Sylvia Lea and Paul Breslin, masters students, are beginning the design and implementation of an interactive system for set design. This work is being undertaken in conjunction with Mark Kelman of the Drama Department. The system is intended for classroom use and, ultimately,



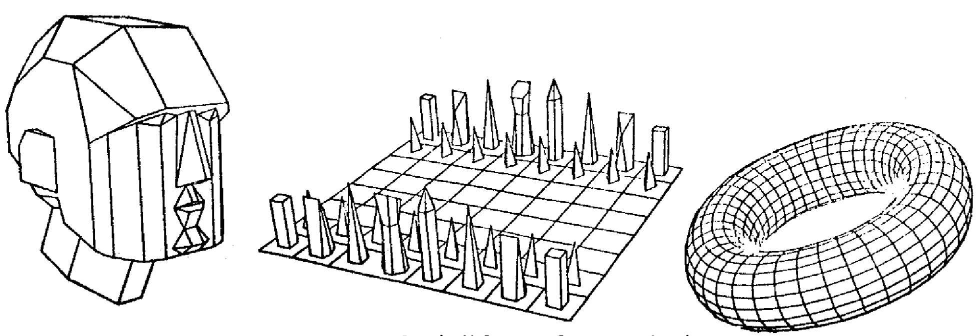
Sequencing rapidly through these images gives the illusion of motion.



A wire-frame rendering.



A haloed rendering.



A visible surface rendering.

as an aid to Canadian theatre companies in analysing the compatibility of possible set layouts with various theatres. Sylvia will be responsible for the data base and for the human interface, while Paul will be responsible for the display algorithms. We expect that the user will perform layout, and select a viewpoint, by manipulating a wire-frame representation of the scene on the E&S system so as to obtain satisfactory interactivity. A high quality color shaded image would then be generated quickly on the Ikonas display.

Computer Aided Design.

A natural extension of our interest in spline techniques for documentation graphics and in visible surface display techniques is to CAD. The obvious deficiencies of polygonally modelled objects make techniques based on Bernstein and B-spline approximation theory attractive.

We are particularly interested in the Beta-spline adaptation of B-splines introduced recently by Brian Barsky. This is an extension of cubic B-spline theory which offers additional parametric control over the tangent and curvature vectors at knots, thus increasing the ease with which a user may control the shape of a curve or surface.

The interactive design of higher order surfaces is best done on a calligraphic display such as the Evans and Sutherland Multi-Picture System, in which the matrix multiplication hardware can be utilized to generate higher order curves at high speed by forward differencing. Having positioned the control points and/or modified the beta parameters associated with each, the Ikonas would then be utilized to generate a high quality shaded image.

We have also been exploring algorithms for working with winged-edge object descriptions, which are computationally attractive even though they are polygonally based.

Results of this work may, of course, prove useful in some of the other projects we have described.

Scoring Dance Choreography.

An inter-disciplinary project with Rhonda Ryman of the Dance Department and Robin Hughes, a choreologist with the Canadian National Ballet, has been undertaken by Baldev Singh. The initial objective is to develop interactive software for scoring dance using Benesh notation. A prototype system, whose principal purpose is to generate feedback from potential users, is being implemented on the Ikonas, but we intend that a second and more flexible cut at the system be done on the Evans & Sutherland equipment because of the need for relatively high precision, large numbers of small vectors, and interactivity.

Similar systems using Labanotation, a different technique for scoring choreography, are underway in the Systems Design Department at Waterloo and at Simon Fraser University. The National Ballet prefers Benesh notation because of its more widespread usage.

The prototype software is being designed with the expectation that we will subsequently want to add semantic routines which check for inconsistencies in the score, and perhaps implement simple animated stick figures from the score to help verify the input. Full scale "natural looking" animation of the input is a very substantial research project which likely will be postponed to a subsequent masters project.

One of the main goals of this project is to gain the experience necessary to write the specifications for a production system which could be installed at the National Ballet.

Antialiasing.

Raster technology has a number of advantages over more traditional storage tube and refresh calligraphic technology, particularly in its ability to display smoothly shaded surfaces in color, but the quality of raster images is often inferior in that the edges of solid areas, as well as lines, generally have a jagged appearance which results from representing objects as an array of colored dots or pixels.

It is possible to ameliorate these effects substantially by manipulating the intensity of line or edge pixels. The problem can be considered to arise because one is attempting to reproduce a discretely sampled signal (the picture) containing frequencies too high to be reconstructed correctly on the display. Greg Hill, a masters student, has been investigating various ways of filtering an image to attenuate the offending frequency component to improve the resulting display.

This work is pertinent to the display of images on any of our raster displays, such as the Telidon terminals, and potentially to the personal computer "workstation" being developed by the Software Portability Group.

The Ikonas Micro-processor.

While the Ikonas is capable of producing very high quality images, in an interactive environment one immediately encounters difficulties in modifying or recomputing the display fast enough to avoid distracting the user. This problem is exacerbated by the fact that the user of a calligraphic display expects to modify only lines, which can be done quite rapidly, while the user of a raster display expects to be able to modify areas on the screen. Performing these computations on a host computer and communicating new intensity values for tens or hundreds of thousands of pixels to the display can be a lengthy process.

One can, or course, purchase or build special purpose hardware for performing such computations more rapidly. A much more flexible solution, however, is to place a high performance dedicated micro-processor close to the display. This was the motivation for ordering the bit-slice micro-processor mentioned earlier. Using such a processor effectively requires some effort since the architecture is highly parallel and computation is controlled by 64-bit-wide micro-instructions of considerable complexity.

Paul Breslin, a masters student, has provided us with a simulator for the Ikonas micro-processor. Implemented in C for the Unix environment, it should greatly facilitate the process of placing the computation intensive portions of various display algorithms in micro-code to increase their speed. The simulator will enable micro-programmers to debug their code interactively in a totally controlled environment before moving the code to the micro-processor itself.

A second masters student, Preston Gurd, recently began work on a SmallC compiler for the micro-processor. Since writing correct micro-programs is a tedious and error-prone activity, the intention is to develop a means by which initialization code can be written in a higher level language so that the micro-programmer can concentrate on directly micro-coding inner loops of the algorithm in question.

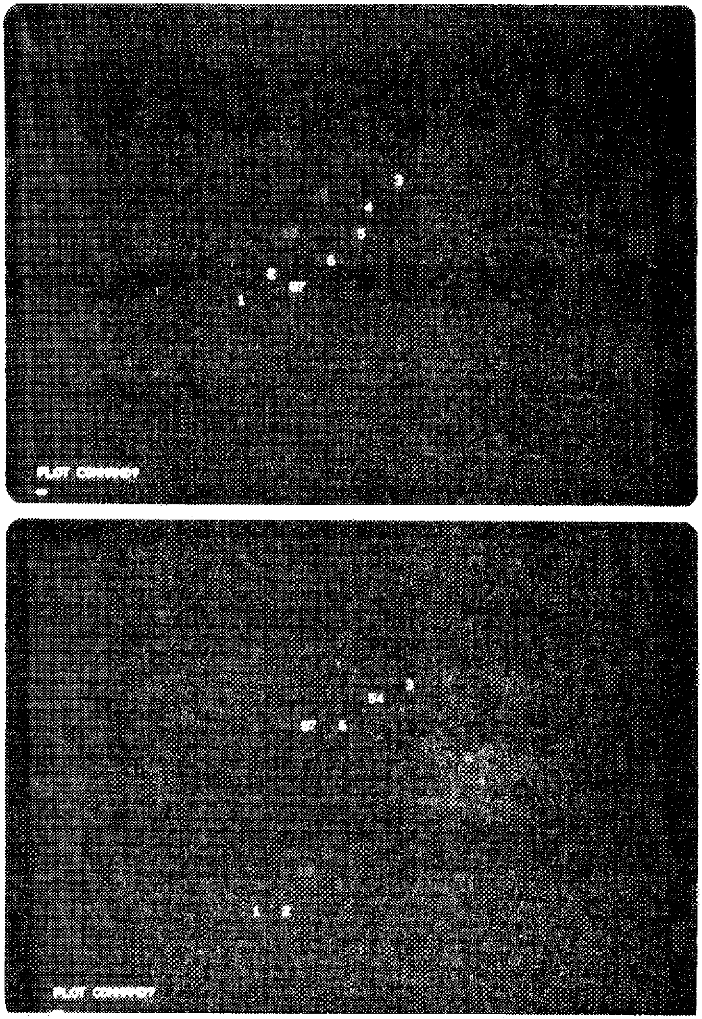
In the longer run we would also like to explore the use of parallel algorithms to speed up display by placing a number of processors on the Ikonas' internal bus.

Cluster Analysis.

Another of our masters students, Rob Stephenson, has completed the initial implementation of an interactive package for analysing clusters in multivariate data [13,14]. The user of CLUSTER is able to specify planes in n-dimensional space onto which the data is projected. The user then suggests a new projection based on a visual examination of the current projection, optionally assisted by the algorithmic analysis performed in a user-supplied subroutine.

Images illustrating such clustering in experimental data appear on the next page. Here six data points represent various measured characteristics of teeth in a species of monkey. Two data points represent measurement of the same characteristics in human teeth, and two data points are from teeth of unknown origin. The clustering which is apparent in the second projection plane shown argues convincingly that the teeth are in fact from a human subject.

Because this project was completed before the Ikonas became available, it presently makes use of relatively low bandwidth graphics terminals such as the Hewlett-Packard 2648A, Tektronix



Points 1-2 are from humans, 3-8 are from monkeys, & 9-10 are unknowns. The top projection shows no clustering, while the bottom does, indicating that the unknowns are human.

4010 or Tektronix 4027. However the software was designed to localize its display dependent features, with the expectation that we would eventually interface it to a display which could be modified rapidly enough to give the user the illusion of "flying" through multi-dimensional space. Since the Ikonas (with a microprocessor) and especially the proposed Evans & Sutherland Picture System should both be sufficient for this purpose, we are looking for a graduate student who would be interested in implementing such extensions to the CLUSTER software.

Debugging.

An obvious area of application for the graphical interaction techniques and ergonomic principles in which we are interested is to the debugging of the programs which embody these techniques and principles. Indeed, by their very nature graphics programs are likely to make use of complex linked data structures and list processing algorithms whose correctness is difficult to verify. Consequently we are exploring the design of interactive debugging systems specifically tailored for the graphics environment.

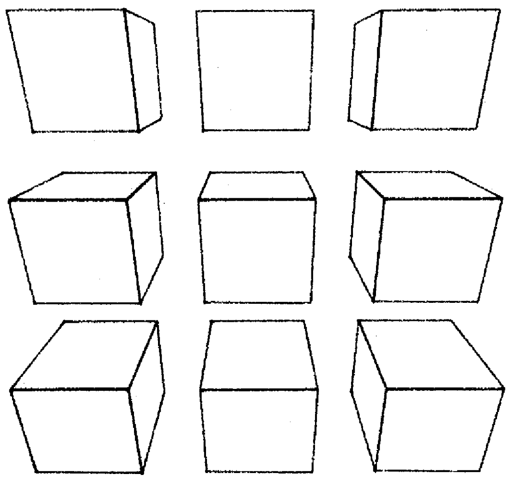
Our first project of this sort was undertaken by Andrei Taramina, an undergraduate, who implemented a means of displaying and manipulating the linked list structures with which we represent three dimensional scenes in the CS 488 graphics package described earlier. An example of a simple such scene and a display generated by Andrei of the data structure describing it appear on the next page.

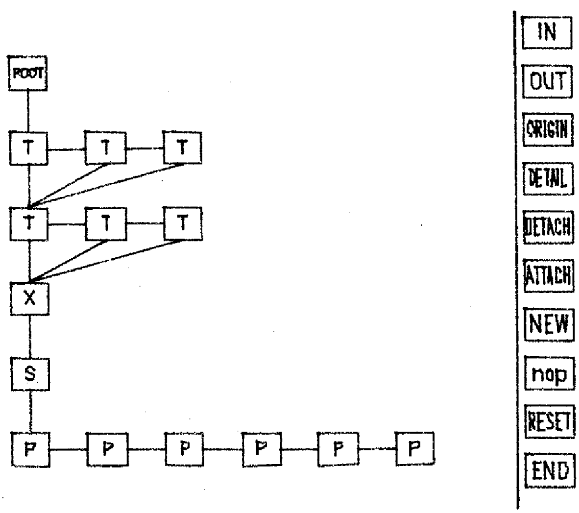
This software determines how to represent such a scene graph (or part of it) on a display terminal. It accepts as input our standard textual representation of a scene graph, and allows us to move around in the graph, examining and modifying node linkages and the data values associated with each node.

A further and much more comprehensive examination of graphics debugging has been undertaken by Edward Bulman, a PhD student. His goal is to design and implement a system, in a Pascal environment, for interactively and graphically debugging graphics programs having arbitrary data structures. The motivation, of course, is to provide ourselves with a general purpose tool which we can use elsewhere in the laboratory in developing graphics algorithms.

Data Analysis Using Density Slicing.

Data from the Ontario Cancer Institute being studied by researchers in the Systems Design Department has been displayed on the frame buffer system using pseudo-color (density slicing) to highlight ultrasonic scan data. This is a very powerful technique for analyzing such data. Interactive programs are being developed by Guy Middleton, an undergraduate student in Physics using software written by members of the Computer Graphics Laboratory.




ROOT
T
T
T
T
T
T
X
S
P
P
P
P
P
P
IN
OUT
ORIGIN
DETAIL
DETACH
ATTACH
NEW
nop
RESET
END

Guy will use these programs as part of a project on automated testing of polycrystalline silicon samples and solar cells being conducted by Prof. Ted Dixon of the Physics Department. Similar applications exist in the system being developed by Prof. Malcolm in conjuction with QA Laboratories. We plan to use our system to demonstrate the feasibility of adding such features to the commercial system currently under design.

Outside Activities

For the last four years we have conducted a two day tutorial on Introductory Computer Graphics at the annual conference of the ACM Special Interest Group on Graphics (Siggraph). Siggraph is the principle North American organization embracing activity in graphics and interaction techniques. Last year the conference attracted some 2,400 people to the technical sessions, and approximately 6,000 people to the vendors' exhibits. The Introductory Graphics Tutorial generally has an attendance of 160-200 people.

We have conducted appropriately modified in-house versions of this tutorial for Burroughs Corporation, Imperial Oil, and Tektronix. We have begun preparing a 5-day version, which will be given at the University of Waterloo next spring. It will be organized around the Telidon terminals we have been given by Electrohome, and conducted for the benefit of people in local industry. The proceeds will be used to fund student conference travel, and to buy equipment for the Laboratory.

Profs. Beatty and Booth also gave a half-day presentation entitled "Computer Graphics - What's Happening" at the 1980 Conference of the Canadian Society for Computational Studies of Intelligence. Prof. Beatty gave an invited talk on "Color in Computer Graphics" at the May 1980 meeting of the Statistical Society of Canada. The latter talk has been expanded into a paper which has been submitted for publication. [10]

Members of the Laboratory handled local arrangements for the Seventh Conference of the Candian Man-Computer Communications Society, which was held at the University of Waterloo in June of this year, and Profs. Beatty and Booth have been appointed General Conference Co-Chairmen for the 1983 Siggraph Conference, which will be held in Detroit.

Three members of the Laboratory (Prof. Beatty, Prof. Booth and Larry Matthies) have worked with Tektronix, Inc. in the design and implementation of a high performance 3D graphics processor [4,8,9,10,12].

Student Support

We absolutely require that students interested in joining the Graphics Laboratory take the Introductory Graphics Class. Students who have satisfied this pre-requisite are encouraged to consider an undergraduate reading course in graphics (CS 499), masters essay or thesis, or PhD research, as appropriate.

For those students who require financial support, a teaching assistantship is available each term for CS 488. A limited number of research assistantships are also available. Contract work is being negotiated with various companies.

The position of "Laboratory Manager," which is supported by a judicious combination of TA and RA money, is also occasionally open. The Lab Manager is responsible for the day-to-day operation of the Laboratory. Duties involve seeing to the repair of equipment, conducting demonstrations and tours of the facility, general software maintenance, and coordinating the work of Laboratory members so that the fruits of their labor may be readily accessed by others.

ALL members of the Laboratory are expected to perform a fair share of the miscellaneous dog-work necessary to keep things running smoothly, and to assist the Lab Manager appropriately.

It is also crucial to the long term success of the Laboratory that all members design and document their work so that it is readily usable by others and can be easily maintained after their departure. No project will be considered complete until a demonstration of it has been prepared and documented.

For students making satisfactory progress the Laboratory contributes towards the cost of attending the annual Siggraph Conference.

The Future

In anticipation of future funding, we gather together here in order of importance a list of the equipment which we feel is needed by the Computer Graphics Laboratory.

For teaching:

- Two to four low cost refresh calligraphic displays, for illustrating the fundamentals of this technology in CS 488 (approximately $15,000 each);

- A low cost, low resolution color impact or ink jet printer, for obtaining colour output from the newly acquired Telidon terminals (approximately $10,000).

For research:

- a high-performance refresh calligraphic display, with full transformation and clipping hardware and appropriate peripherals (approximately $150,000);

- call-in and call-out equipment, either for the VAX or for the 11/45, so that we may communicate with other installations, and transfer files, via the uucp network (approximately $4,000 - Vadic and Abel equipment appears to be cheaper and better than DEC equipment);

- an incremental pen plotter, for obtaining high-quality line output from various graphics programs, especially from those which create images on calligraphic equipment (approximately $6,000 - the HP 7221B appears to be the best choice).

Finally, it should be noted that all of this equipment and the personnel to use and maintain it will require space. The Laboratory is currently almost filled and with the remainder of the equipment on order will need to expand into the last remaining space within the building. The purchase of additional equipment will require that additional space be found.

Summary

In the last few months the Computer Graphics Laboratory has reached critical mass, both with respect to personnel and equipment. The arrival of our Ikonas System (courtesy of NSERC), dedicated use of the PDP 11/45 (courtesy of the Mathematics Faculty Computing Facility), the gift of seven Telidon terminals by Electrohome, and contributions from the Department, the Math Faculty and the University Academic Development Fund towards tablets, video tape equipment and the proposed E&S System have made the Laboratory a viable, thriving concern. Our students are eager to participate in a large variety of projects. The recent purchase of a VAX 11/780 by MFCF will contribute substantially to a quality teaching environment compatible with our research environment. If we are successful in obtaining some calligraphic equipment we will have all of the essential ingredients necessary for a flexible program of research, development and education in computer graphics, both within the University and in conjunction with industry.

We are very grateful for the support we have received - and hopeful of more in the future!

References

[1] Richard J. Beach, John C. Beatty, Kellogg S. Booth, and Alex R. White, "Documentation Graphics at the University of Waterloo," International Conference on Research and Trends in Document Preparation Systems, pp. 123-126 (28-29 February 1981).

[2] John C. Beatty, PICTURE - A Picture-Drawing Language for the TRIX/RED Report Editor, Lawrence Livermore National Laboratory Report UCID-30156 (1979).

[3] John C. Beatty, "A Tutorial on Raster Graphics and Colour," submitted to The American Statistician.

[4] John C. Beatty, A Graphics Package for the CRG Frame Buffer, Technical Report CR-80-8, Applied Research Group, Tektronix Laboratories, Beaverton, Oregon 97077.

[5] John C. Beatty and Kellogg S. Booth, "Teaching Computer Graphics at the University of Waterloo," Proceedings of the 89th Annual Conference of the American Society for Engineering Education, volume 1 pp. 214-220 (21-25 June 1981).

[6] John C. Beatty, Kellogg S. Booth and Larry H. Matthies, "Revisiting Watkins' Algorithm," Proceedings of the Seventh Annual Conference of the Canadian Man-Computer Communications Society, pp. 359-370 (10-12 June 1981).

[7] John C. Beatty, Janet S. Chin and Henry F. Moll, "An Interactive Documentation System," Computer Graphics 13:2 pp. 71-82 (August 1979).

[8] Jay W. Beck and John C. Beatty, Special Purpose Geometry Processor Functional Specification, Technical Report CR-80-14, Applied Research Group, Tektronix Laboratories, Beaverton, Oregon 97077.

[9] Kellogg S. Booth and Marc Wells, Geometry Processor Micro-Code Documentation, Technical Report CR-80-7, Applied Research Group, Tektronix Laboratories, Beaverton, Oregon 97077.

[10] Larry H. Matthies, FBLIB - The Frame Buffer Support Library, CRL PDP-11/70 online documentation FBLIB(7), Applied Research Group, Tektronix Laboratories, Beaverton, Oregon 97077.

[11] Larry H. Matthies, Scanning Algorithms for Computer Graphics, Master's Essay, Department of Computer Science, University of Waterloo (1981).

[12] Ben McCann and Larry H. Matthies, The CRG Frame Buffer, Technical Report CR-80-16, Applied Research Group, Tektronix Laboratories, Beaverton, Oregon 97077.

[13] R.B. Stephenson, Interactive Graphic Analysis For Multivariate Data Masters Thesis, Department of Computer Science, University of Waterloo (1981).

[14] Robert B. Stephenson, John C. Beatty and Jane F. Gentleman, "Interactive Cluster Analysis for Multivariate Data," Proceedings of the 14th Annual Symposium on the Interface," (March 1981).

[15] Alex R. White, Pic: A C-Based Illustration Language, Masters Thesis, Department of Computer Science, University of Waterloo (1981).