Exam Instructions (Read Carefully)
1. Print your Name and Student Identification Number on every page of the exam in the space provided at the top of each page immediately.
2. Sign the first page of the exam with your Signature in the space provided on the upper left immediately.
3. Continue reading the instructions, but do not open the exam booklet until you are told to do so by a proctor.
4. Cheating is an academic offense. Your signature on the exam indicates that you understand and agree to the University’s policies regarding cheating on exams.
5. Please read the entire exam before answering any of the questions.
6. There are three questions on this exam, each worth the indicated number of marks. Answer as many questions as you can.
7. Write all of your answers on these pages. If you need more space, there is blank space at the end of the exam. Be sure to indicate when a question is continued, both on the page for that question and on the continuation page.
8. Interpret the exam questions as written. No questions will be answered by the proctors during the exam period.
9. The exam is closed book. You may not use any aids.
10. You have 45 minutes in which to work. Budget your time wisely.
11. In the event of a fire alarm during the exam, enter the four-character code provided by the proctor(s) in the space on the upper right, then gather your belongings and exit the room, handing your exam to a proctor as you exit.
12. No one will be permitted to leave the exam room during the last ten minutes of the exam.
**Question #1 (40 marks – 2 marks each)**

This question tests your knowledge of light, human colour vision, colour systems, and CRTs. For each of the following, check the appropriate box to indicate whether the statement is generally **True** or generally **False**. Wrong answers count negative, so don’t guess.

<table>
<thead>
<tr>
<th>True</th>
<th>False</th>
<th>Statement (+2 for correct answers, –2 for incorrect)</th>
</tr>
</thead>
<tbody>
<tr>
<td>✗</td>
<td></td>
<td>The <em>spectrum</em> of a light source determines the colour that will be perceived under controlled viewing conditions.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>The <em>energy</em> (voltage) of the electron beam in a CRT determines the colour of the light that will be emitted by the phosphor.</td>
</tr>
<tr>
<td>✗</td>
<td></td>
<td>In the human visual system, the <em>luminance</em> of a colour is largely dependent on the response of the red and green cones, and much less dependent on the response of the blue cones.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>Each type of phosphor in a CRT has only a single wavelength that is emitted during <em>phosphorescence</em>.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>Each type of phosphor in a CRT has only a single wavelength that is emitted during <em>fluorescence</em>.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>In the human visual system, the <em>rods</em> are only sensitive to photons of white light.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>In the human visual system, the <em>green cones</em> are only sensitive to photons of green light.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>The conversion between the CIE XYZ colour system and the HSV colour system is a linear transformation.</td>
</tr>
<tr>
<td>✗</td>
<td></td>
<td>The conversion between the CIE XYZ colour system and the YIQ (NTSC) colour system is a linear transformation.</td>
</tr>
<tr>
<td>✗</td>
<td></td>
<td>Two spectral distributions that are perceived to be the same colour are called <em>metamers</em>.</td>
</tr>
<tr>
<td>True</td>
<td>False</td>
<td>Statement (+2 for correct answers, −2 for incorrect)</td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>✗</td>
<td>✓</td>
<td>The <em>persistence</em> of a phosphor is the time it takes for phosphorescence to decay to 10% of its original intensity.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>The <em>pitch</em> of a CRT is the spacing between pixels as measured on the screen.</td>
</tr>
<tr>
<td>✗</td>
<td>✓</td>
<td>High performance CRTs, such as those used in line drawing displays, often employ more expensive <em>electrostatic deflection systems</em> to obtain better speed and accuracy, but most monitors use the cheaper <em>electromagnetic deflection systems</em>.</td>
</tr>
<tr>
<td>✗</td>
<td>✓</td>
<td>The <em>accelerating system</em> is always electrostatic, never electromagnetic.</td>
</tr>
<tr>
<td>✗</td>
<td>✓</td>
<td>The <em>focusing system</em> is usually electromagnetic, but it could be electrostatic.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>The source of electrons in a CRT is the <em>filament</em>, which produces electrons when a high voltage (10KV to 25KV) is applied to it.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>The <em>update rate</em> is always at least as fast as the <em>refresh rate</em> for a CRT in order to avoid <em>critical fusion frequency</em>.</td>
</tr>
<tr>
<td></td>
<td>✗</td>
<td>Monitors for computer graphics are more expensive than regular television sets because the difficult-to-manufacture (and thus very costly) phosphors used for computer graphics must provide a <em>gamut</em> that contains the entire CIE chromaticity diagram.</td>
</tr>
<tr>
<td>✗</td>
<td>✓</td>
<td>The muscles that control <em>focusing</em> in the eyes are affected by the muscles that control <em>vergence</em> in the eyes.</td>
</tr>
<tr>
<td>✗</td>
<td>✓</td>
<td>The muscles that control <em>vergence</em> of the eyes are affected by the muscles that control <em>focusing</em> in the eyes.</td>
</tr>
</tbody>
</table>
Question #2 (20 marks − 5 marks each)

This question tests your knowledge of the tristimulus theory of colour vision and colorimetry as it was used in Assignment #1, and how these concepts explain some visual illusions.

Imagine that an illustration of the Nulling of Apparent Motion is presented on a laser display by cycling through the following four images in a rectangular display window, where “B” is black, “W” is white, “R” is red, and “G” is green. You may assume that the display is produced by shining the red, green and blue lasers onto the coloured regions of an image and that each laser is either all the way “on” or all the way “off” (i.e., the frame buffer has one bit at each pixel for each of the red, green and blue components).

<table>
<thead>
<tr>
<th>$t_i$</th>
<th>B</th>
<th>W</th>
<th>B</th>
<th>W</th>
<th>B</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{i+1}$</td>
<td>R</td>
<td>G</td>
<td>R</td>
<td>G</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>$t_{i+2}$</td>
<td>W</td>
<td>B</td>
<td>W</td>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{i+3}$</td>
<td>G</td>
<td>R</td>
<td>G</td>
<td>R</td>
<td>G</td>
<td></td>
</tr>
</tbody>
</table>

Figures 11.9 is reproduced from the text on the next page. Answer the following questions by referring to that figure when necessary.

The following data can be read from Figure 11.9.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\lambda = 520$</th>
<th>$\lambda = 620$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(\lambda)$</td>
<td>0.058</td>
<td>0.100</td>
</tr>
<tr>
<td>$G(\lambda)$</td>
<td>0.150</td>
<td>0.027</td>
</tr>
<tr>
<td>$B(\lambda)$</td>
<td>0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>$L(\lambda)$</td>
<td>0.210</td>
<td>0.27</td>
</tr>
<tr>
<td>$L'(\lambda)$</td>
<td>0.060</td>
<td>0.00</td>
</tr>
</tbody>
</table>

For $\lambda = 520$ (the "G" laser) and $\lambda = 620$ (the "R" laser) the red, green and blue spectral response functions sum to the luminous efficiency function (which is essentially the ‘‘brightness’’), denoted by $L(\lambda)$ in the table above. For a person with no green cones, the modified $L'(\lambda)$ function, which is the sum of only the red and blue spectral response functions without the green spectral response, gives the perceived brightness.

(a) If the display uses equal-power lasers for each of red, green, and blue with the red laser having a wavelength of $\lambda = 620$ and the green laser having a wavelength of $\lambda = 520$, which direction would the squares appear to move for a person with normal colour vision?

The squares appear to move to the RIGHT because $L(520)$ is brighter than $L(620)$ and thus R is associated with B and G with W, giving the illusion of movement to the right.

5 marks for "RIGHT", 1 mark for "LEFT", no marks for anything else.

(b) If you wanted to null the apparent motion for a person with normal colour vision, by what multiplicative factor should the power of the red laser be changed? (State clearly whether there should be an increase or a decrease and give the required factor as a multiplier on the current power level. Your estimate of the factor should be within about 10% of the correct answer to receive full marks.)

If the intensity of red is INCREASED by a factor of 1.7, the ratio $L(520)/L(620)$, the two will be equiluminant and the apparent motion
will cease.

5 marks for anything in the range 1.5 to 1.9, then minus one mark for each 0.1 plus or minus that (i.e., 2.2 gets 2 marks because it is 0.3 greater than 1.9).

-1 mark for not saying INCREASED, or at least something similar.

(c) If a person with no green cones looked at the display, which way would the squares appear to move?

The squares appear to move to the LEFT because $L'(620)$ is brighter than $L(520)$, so this time G is associated with B and R is associated with W, giving the illusion of movement to the left.

5 marks for "LEFT", 3 marks for "THE OPPOSITE OF (a)", 1 mark for "RIGHT", no marks for anything else.

(d) If you wanted to null the apparent motion for a person without any green cones, by what multiplicative factor should the power of the red laser be increased or decreased (and by how much)?

If the intensity of red is DECREASED by a factor of 0.60, the ratio $L'(520)/L'(620)$, the two will be equiluminant and the apparent motion will cease.

5 marks for anything in the range 0.5 to 0.7, then minus one mark for each 0.1 plus or minus that (i.e., 0.1 gets 1 mark because it is 0.4 less than 0.5).

-1 mark for not saying DECREASED, or at least something similar.

Note: The factors for Parts (b) and (d) are just about reciprocals of each other, so the relative luminance levels are almost exactly reversed!

Marking Notes:

- if the correct numerical answer was given for any reason, you got full marks - even if the reasoning was way off.

- if the answer was expressed as a ratio, without actually doing the division, but it looked like the right reasoning was used to get the numerator and denominator, the marker calculated the result, and gave a mark appropriate to the result, then subtracted 1.

- if students didn’t do the division, and in addition seemed to have the wrong numbers in the numerator or denominator, the marker gave them nothing (even if doing the division would have yielded the correct numerical result).

Summary: if the reasoning was right, students either got full marks or lost 1. If the reasoning was wrong but they calculated a numerical answer, they were scored according to the marking sheet. If they reasoned wrong *and* didn’t do the division, they got
nothing)

- It wasn’t clear from the question exactly what form the number should be in, so forms were converted whenever it seemed clear what the student meant. So:

  "increase by 35%" becomes 1.35
  "decrease by 60%" becomes 0.4
  "decrease by a factor of 1.33" becomes 0.67

- There was no penalty for using any of these alternate forms.
See Figure 11.9 in the textbook.

**Figure 11.9** The spectral-response functions of each of the three types of cones in the human retina plotted as a function of wavelength assuming equal power for all wavelengths.
Question #3 (40 marks – 2 marks each)

Explain the following terms as they have been used so far in our course on computer graphics. If the term is an acronym, explain for what it is an acronym and its meaning, usage, or how it functions (i.e., do not just provide the full name, but also explain what the acronym identifies).

(a) **addressability**

The number of spots (pixels for a raster display) that can be specified in x and y (these need not be the same). This is not the same as resolution, which is essentially the number of spots (or line pairs) that can actually be distinguished when they are displayed.

(b) **aliasing**

Visual artifacts such as the "jagged" corners on lines or characters that result from the requirement that only pixels at integral coordinates be displayed, which is an inherent problem when continuous signals (images) are approximated by discrete samples.

(c) **bitmap**

A digital representation of an image as a rectangular array of pixels, usually with a single bit (0 or 1) per pixel, but often extended to include more general bitmaps in which multiple bits per pixel are used.

(d) **calligraphic display**

A "line drawing" or "vector" display in which points, line segments and possibly curve segments (such as conic sections) are drawn directly by the hardware (as opposed to a raster or bitmap display).

(e) **Doug Engelbart**

The inventor of the mouse and various other ideas now prevalent in desktop systems. Engelbart led a group at SRI (Stanford Research Institute), in which many people who later went to Xerox PARC, Apple and other companies first learned about these ideas.

(f) **frame buffer**

The hardware that implements a bitmap in which memory is addressed using (x,y) addresses that correspond to pixel locations on the screen (this depends on the addressability of the frame buffer) and every pixel has one or more bits associated with it, sometimes considered to be multiple fields (such as the R, G, and B fields in a "full colour" 24-bit frame buffer).
(g) **glVertex3f()**

The OpenGL function that adds a single 3-D point to the current graphic object (line, curve, polygon, surface mesh). Points are described by three floating point numbers, one for each of the x, y and z coordinates.

(h) **graphics pipeline**

The name given to the total process through which an abstract representation of a scene or object (usually a data structure that is designed specific to a particular application) is sequentially transformed into various intermediate representations that capture the geometry and other properties, ultimately into a bitmap representation in the frame buffer, then to analog voltages to the CRT and finally light sensed by the eye and processed by the human visual system.

(i) **Grassman’s Laws**

The laws of linear algebra for vector spaces (associativity, commutativity, symmetry, etc.) that were determined to apply to the colour matching process in human vision through experimental evidence gathered in the 19th Century.

(j) **index of refraction**

A measure of the relative speed of light through a material. The index of refraction for a vacuum is 1.0 and the index of refraction for other materials is the ratio of the speed of light in a vacuum to the speed of light in the material.

(k) **Ivan Sutherland**

The person generally credited with laying the foundations of modern interactive computer graphics through his doctoral thesis "Sketchpad" done at MIT in 1963.

(l) **LUT**

A "Look Up Table" is a set of very highspeed (one random access every 10 nanoseconds) hardware registers in which the incoming register address is a colour number (usually a pixel value from the frame buffer) and the corresponding register content is the digital (R,G,B) values that will be displayed for the pixel. Often the LUT is integrated onto a single chip with the D/A converters in the video controller.

(m) **nonspectral colour**

A colour for which there is no single wavelength of light that is the dominant wavelength for that colour. Of the fully saturated colours, those along the "Purple Line" of the CIE Chromaticity Diagram are nonspectral.
(n) odd-parity rule

A way of computing whether a point is "inside" or "outside" a polygon by counting the number of times a line running from infinity to the point crosses the boundary of of the polygon (an odd number of crossings means the point is "inside").

(o) picking

The operation of identifying one or more graphical objects in a display as having been selected by the user. Often this is done using a pointing device to determine an \((x,y)\) location on the screen and then determining through a hardware or software algorithm those objects that are displayed at or near that point (this is "pick correlation"). Some hardware devices (such as the lightpen) perform picking as part of the display process.

(p) polling

Also called "sampling", this is an input technique in which a program queries the "state", "value" or "measure" of an input device (often periodically) based on the decisions made within the program. This contrasts with "event-driven" or "interrupt" schemes in which the device determines when to send information to the program.

(q) simultaneous contrast

The psychophysical phenomenon in which the perceived colour of an area depends on the surrounding colour and various geometric relationships between the area to the surrounding areas (size, separation, etc.).

(r) specular reflection

The "mirror-like" reflection of light from a surface in which the angle of reflection is primarily in a direction equal but opposite to the angle of incidence when measured from the surface normal.

(s) SRGP

The "Simple Raster Graphics Package" is a complete set of, low-level 2-D drawing and input primitives designed for a raster display system. The X Window System offers a similar functionality through a different set of primitives.

(t) triad

A set of three phosphor dots on a (shadow mask) colour monitor, one for each of red, green and blue. In general, these do NOT correspond to a single pixel in the frame buffer.
(extra space to continue work)