VGP352 – Week 1

- Agenda:
  - Course Intro
  - Reading technical papers
  - Curves
  - Curved surfaces
  - Per-fragment lighting revisited
    - Phong Shading
    - Surface-space
  - Bump mapping
    - Basic usage
    - Bumpmap storage

What should you already know?

- C++ and object oriented programming
  - For most assignments you will need to implement classes or portions of classes that conform to specific interfaces
- Graphics terminology and concepts
  - Polygon, pixel, texture, infinite light, point light, spot light, etc.
- Linear algebra and vector math
  - Matrix arithmetic

What should you already know?

- Material from VGP351:
  - Using OpenGL
    - Setting up shaders
    - Getting data in
    - etc.
  - Transformations
    - 3D space transformations
    - Projections
  - Lighting and shading
  - Texture mapping

What will you learn?

- Advanced lighting models
  - BRDFs
  - Fur and hair rendering
  - “Toon” and other non-photorealistic rendering

How will you be graded?

- Four bi-weekly quizzes
  - These are listed on the syllabus
- One final exam
- Three programming projects
  - The first will be pretty small...perhaps small enough to complete in class
  - The remaining two projects will be larger
- One in-class presentation

How will you be graded?

- Keep in mind:
  - There is a *lot more* reading than in VGP351
    - More readings from the textbook
    - Readings from academic papers
  - There is *more* programming than in VGP351

How will programs be graded?

- Does the program produce the correct output?
- Are appropriate algorithms and data-structures used?
- Is the code readable, clear, and properly documented?

How will the presentation be graded?

- During the term, several papers will be assigned to be read
  - Select and present one of the assigned readings to the class
  - Material from some papers may appear on bi-weekly quizzes

Class Web Site

- Syllabus, assignments, and base code:

http://people.freedesktop.org/~idr/2010Q4-VGP352/

Reading Technical Papers

- Why read technical papers?

Reading Technical Papers

- Why read technical papers?
  - Almost every major advance in gaming graphics can be traced to a SIGGRAPH paper from 1 to 10 years before
  - At publication many algorithms are not *yet* usable
    - Hardware isn't quite fast enough / flexible enough
    - Algorithm makes simplifying assumptions that prevent *general* use
- Reading papers *effectively* is a skill

Reading Technical Papers

- Read a paper in 3 passes:
  - 1st pass: the 10 minute overview
    - Read the title, abstract, and introduction
    - Read the section and subsection headings
    - Read the conclusion
    - Scan the references

Reading Technical Papers

- Read a paper in 3 passes:
  - 1st pass: the 10 minute overview
    - Read the title, abstract, and introduction
    - Read the section and subsection headings
    - Read the conclusion
    - Scan the references
  - Answer the “five C's”
    - Category: What type of paper is it?
    - Context: What other work is it related to?
    - Correctness: Is it based on valid / reasonable assumptions?
    - Contribution: What are the main contributions?
    - Clarity: Is it well written?

Reading Technical Papers

- Read a paper in 3 passes:
  - 2nd pass: an hour for details
    - Read the whole paper
    - Carefully examine diagrams, figures, graphs, etc.
    - Skip or skim proofs and detailed equations

Reading Technical Papers

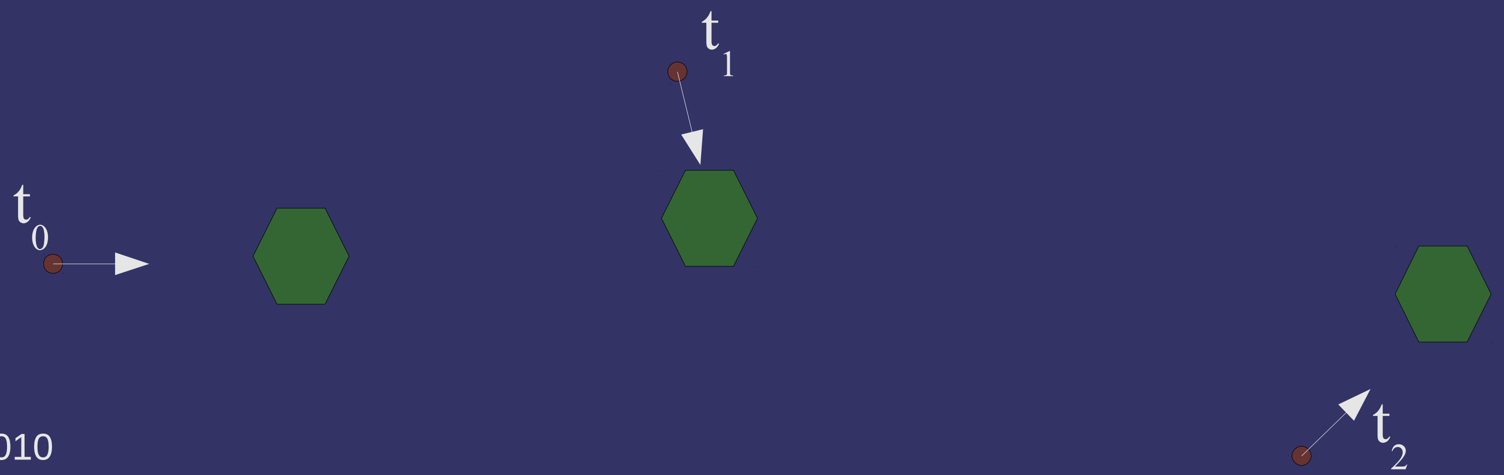
- Read a paper in 3 passes:
  - 3rd pass: re-implement the paper
    - Recreate the work
    - Identify and challenge every assumption in the paper
      - Helps identify *both* the innovations and failings of the paper
    - Compare you recreation with the original
    - Make notes of ideas for future work

References

Keshav, S. 2007. How to read a paper. *SIGCOMM Computer Communications Review.* 37, 3 (Jul. 2007), 83-84. http://www.sigcomm.org/ccr/drupal/files/p83-keshavA.pdf

Camera Control

- How can we move a virtual camera through a series of artist selected positions?



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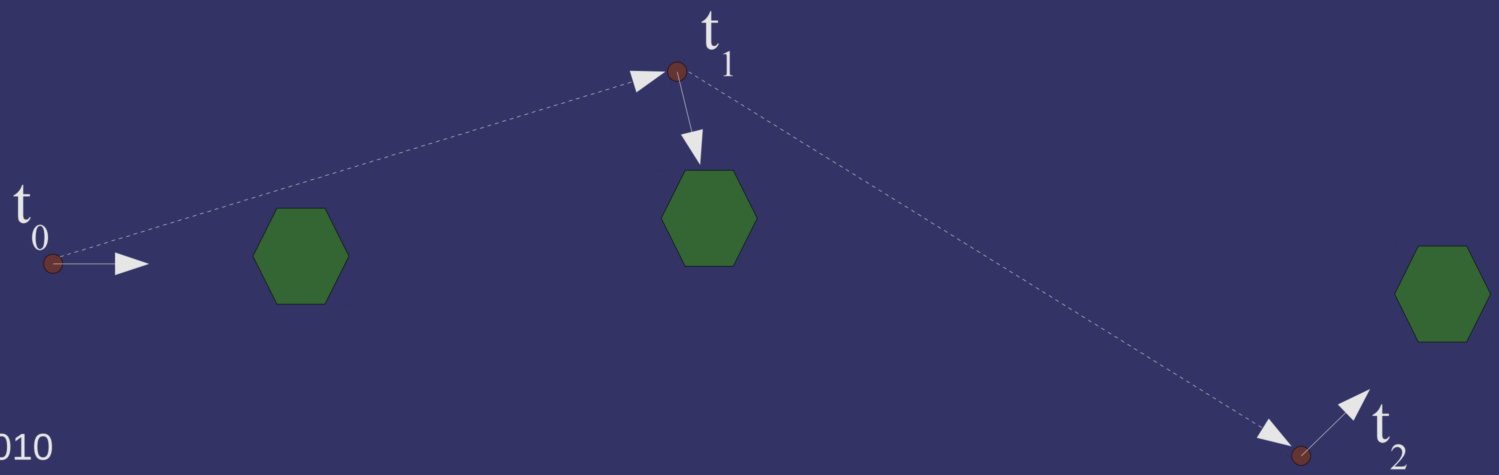
Camera Control

- How can we move a virtual camera through a series of artist selected positions?
  - Linearly interpolate between the positions

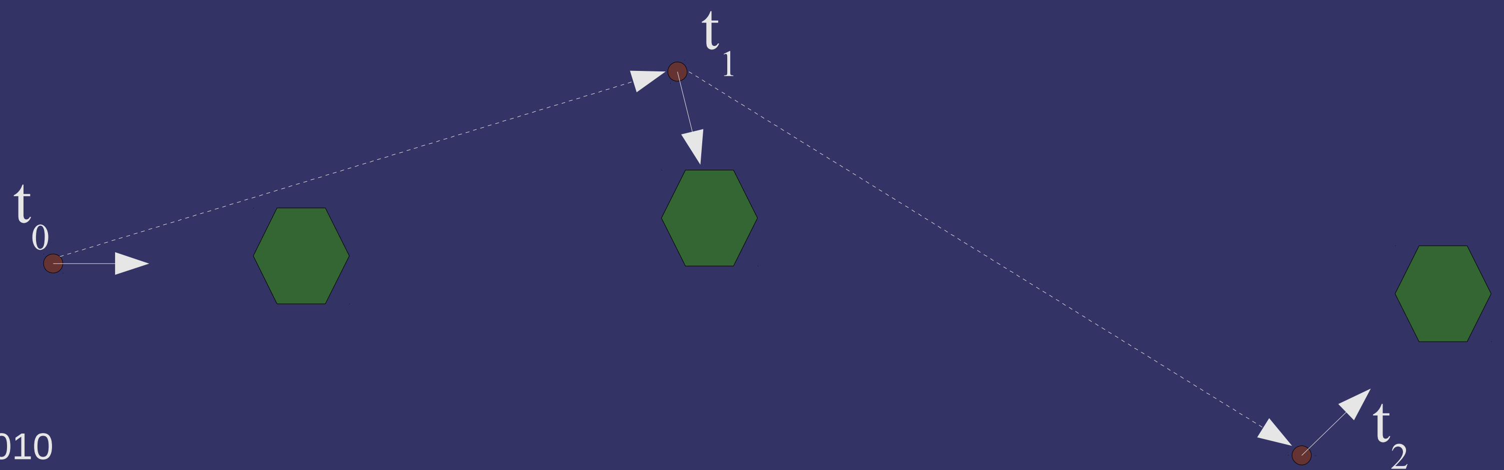
$$
\begin{aligned}
\mathbf{p}(t) &= \mathbf{p}_0 + t(\mathbf{p}_1 - \mathbf{p}_0) \\
&= (1-t)\mathbf{p}_0 + t\,\mathbf{p}_1
\end{aligned}
$$

  - Positionally continuous (aka *C^0 continuity*)



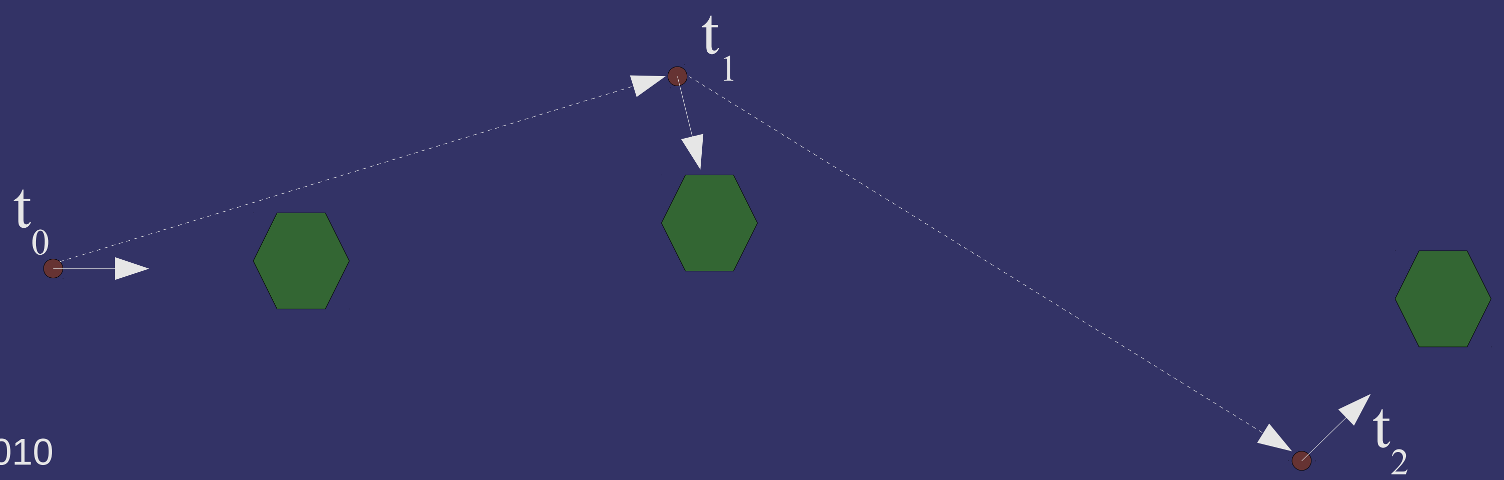
Camera Control

- What's wrong with C^0?



Camera Control

- What's wrong with C^0?
  - Jarring change in direction at control points
  - Jarring change in speed at control points
    - Direction change or speed change = velocity change

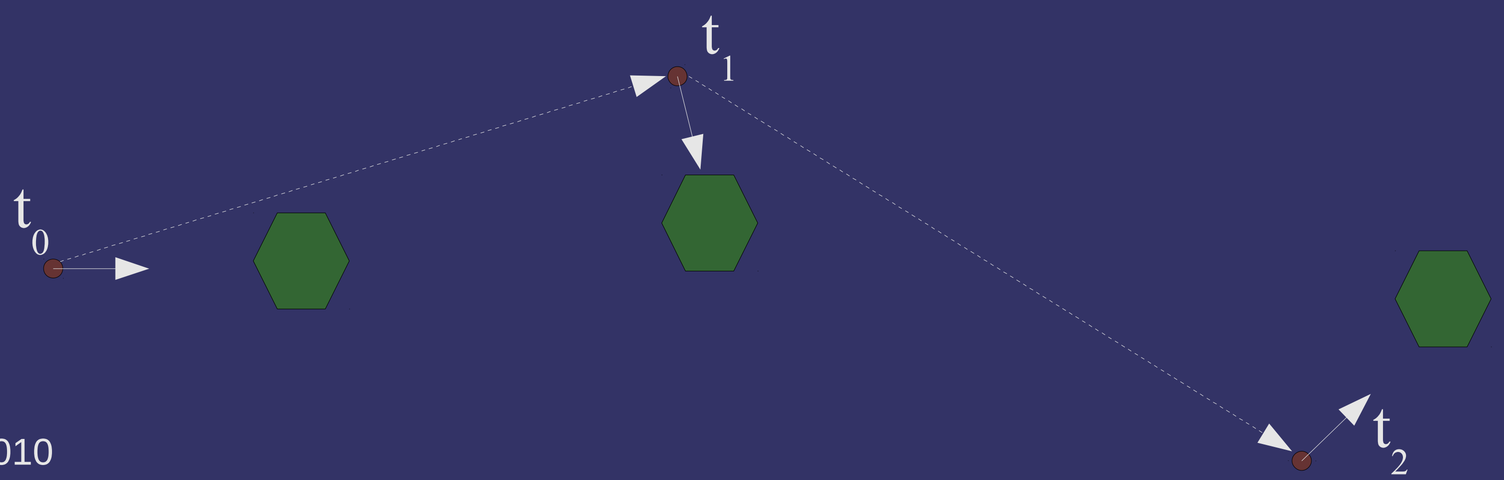


Continuity

- What does it mean?
  - "f is C^0" → The function f is continuous
  - "f is C^1" → The function f' is continuous
  - "f is C^2" → The function f'' is continuous
  - …
  - "f is C^∞" → All derivatives of f are continuous

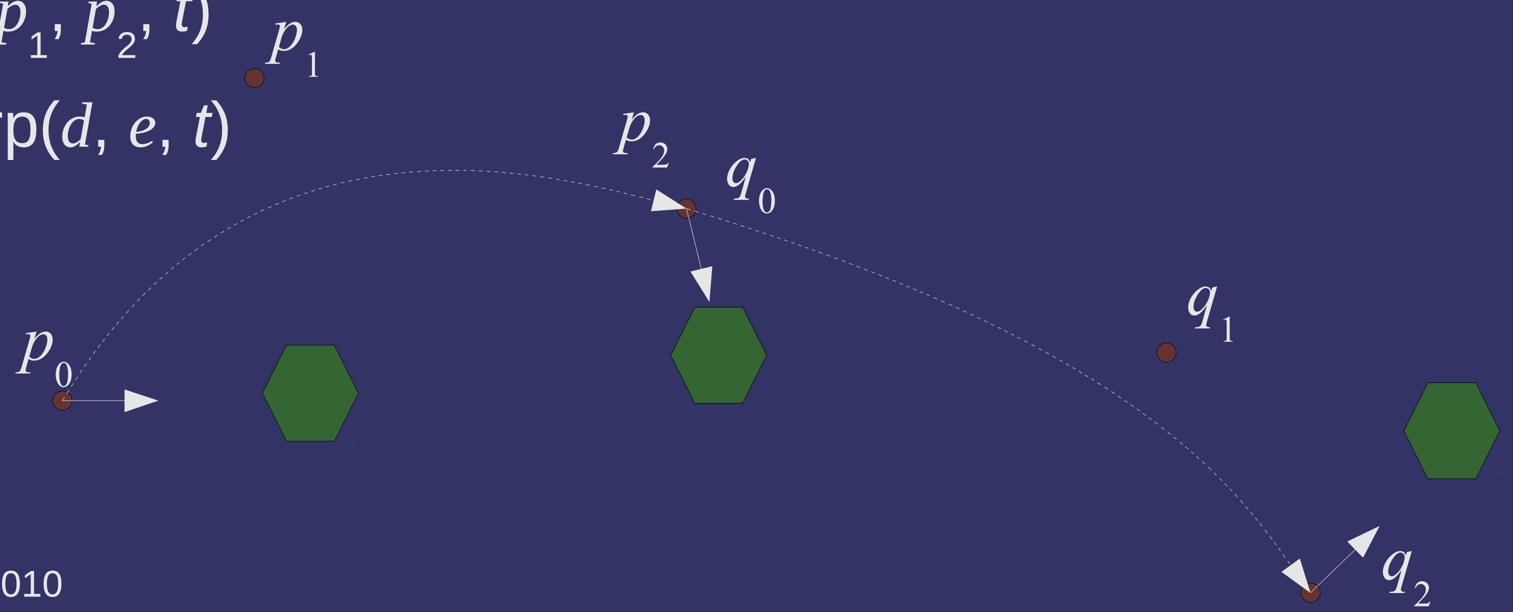
Camera Control

- How can we fix this?



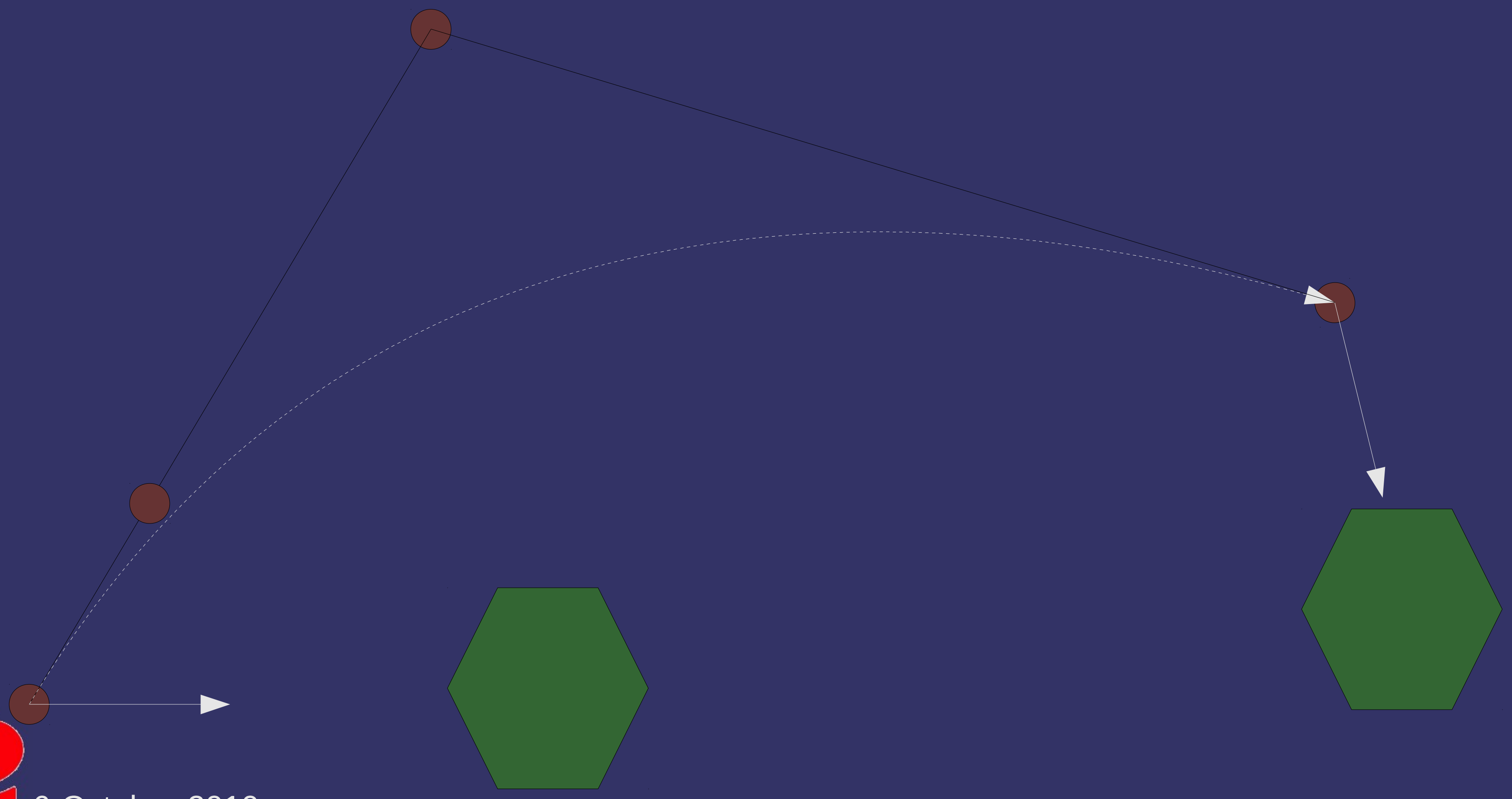
Camera Control

- How can we fix this?
  - Add one more control point for each segment
    - Each segment has p_0, p_1, and p_2
  - Do more linear interpolation
    - $d = \mathrm{lerp}(p_0, p_1, t)$
    - $e = \mathrm{lerp}(p_1, p_2, t)$
    - $\mathrm{p}(t) = \mathrm{lerp}(d, e, t)$



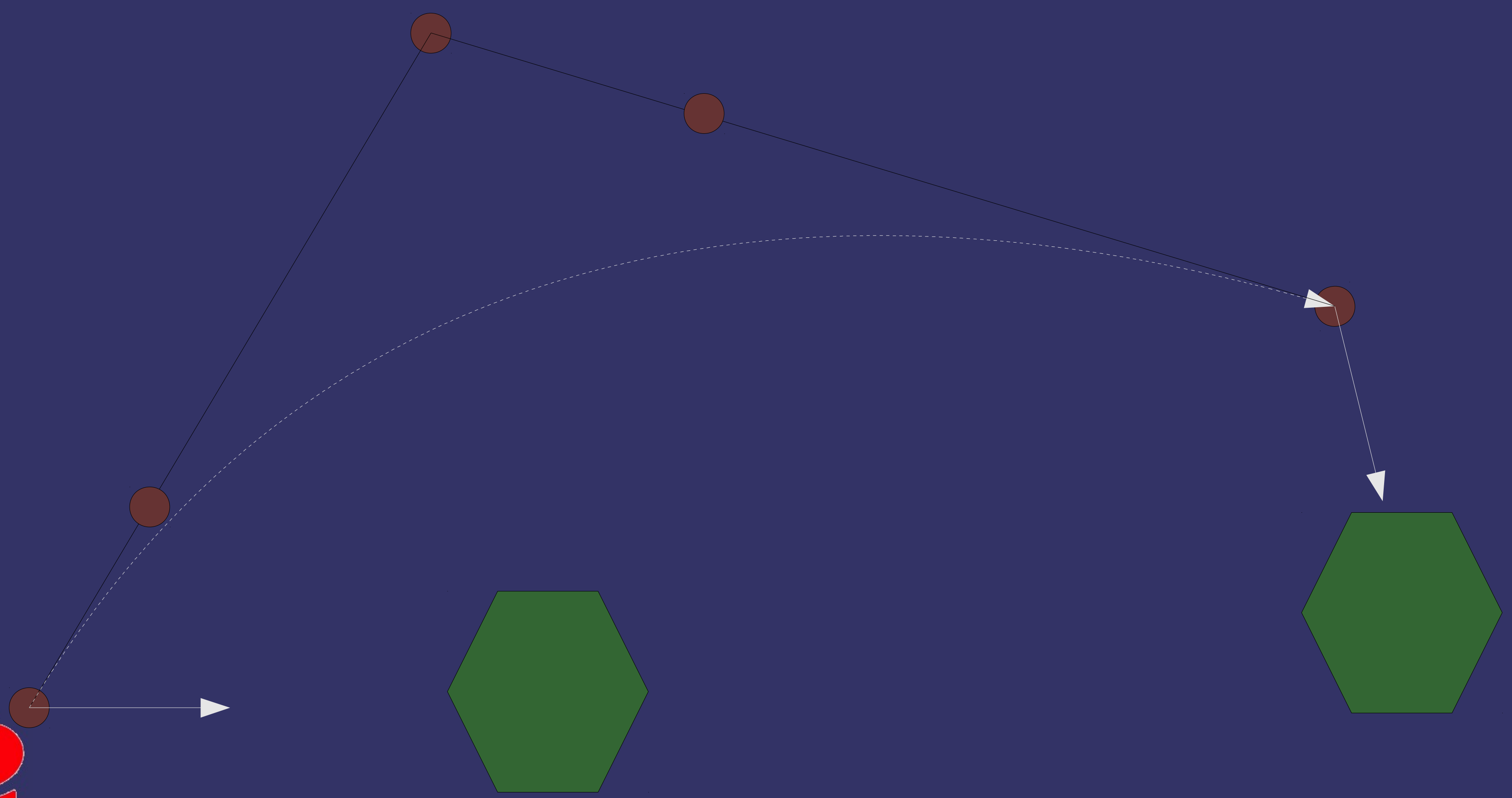
Camera Control

- p(0.3) = lerp(p_0, p_1, 0.3)



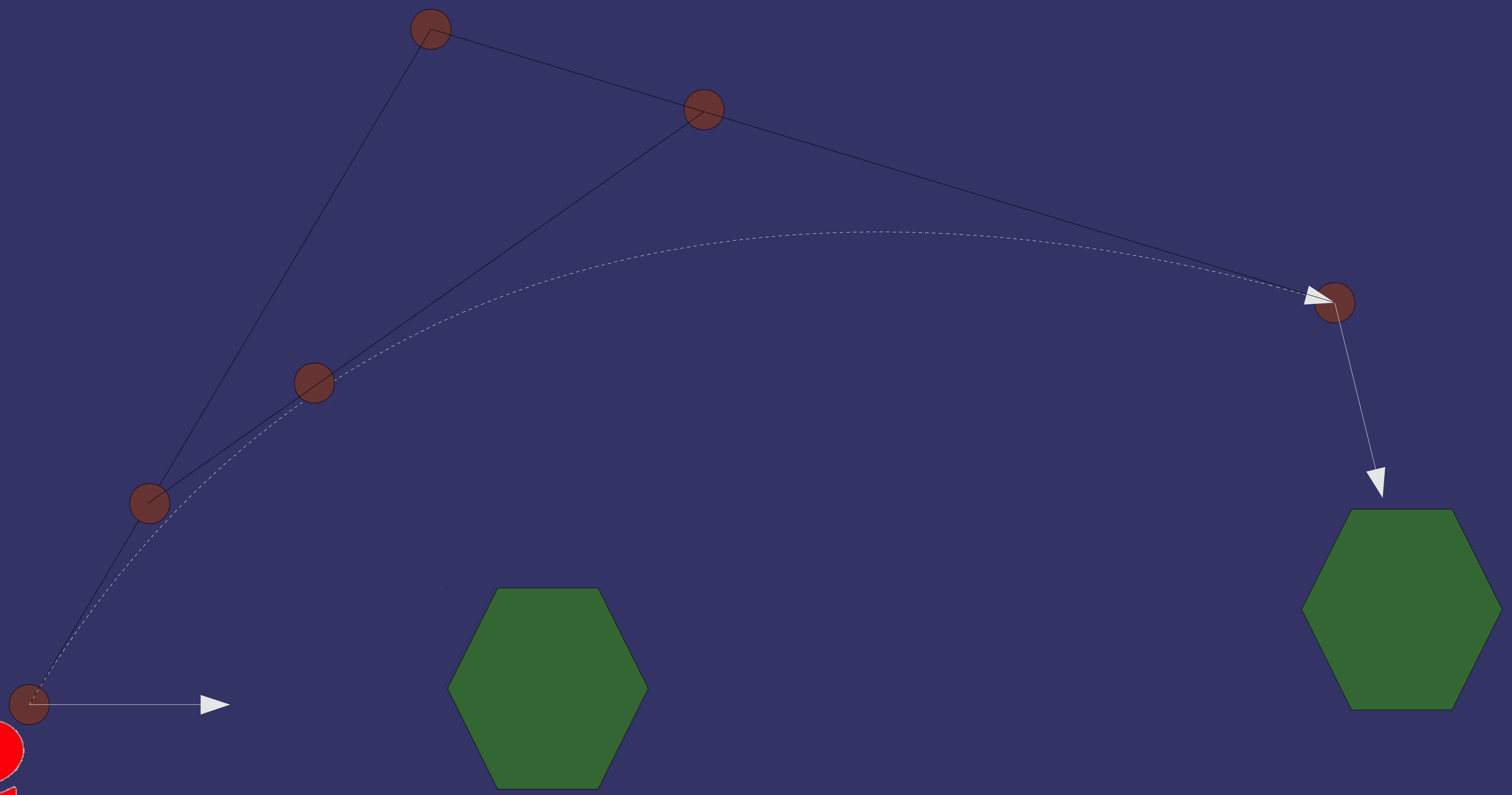
Camera Control

- p(0.3) = lerp(p_0, p_1, 0.3) lerp(p_1, p_2, 0.3)



Camera Control

- $p(0.3) = \mathrm{lerp}(\mathrm{lerp}(p_0, p_1, 0.3), \mathrm{lerp}(p_1, p_2, 0.3), 0.3)$



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Bézier Curve

- This works out to:

$$\mathbf{p}(t) = (1-t)^2 \mathbf{p}_0 + 2t(1-t)\mathbf{p}_1 + t^2 \mathbf{p}_2$$

- More formally:

$$\mathbf{p}_i^k(t) = (1-t)\mathbf{p}_i^{k-1}(t) + t\,\mathbf{p}_{i+1}^{k-1}(t), \begin{cases} \mathrm{k} & = & 1..n \\ \mathrm{i} & = & 0..n-k \end{cases}$$

  - Curve with x control points is degree x-1
    - n is the degree of the polynomial that defines the curve
    - Our curve with 3 control points is degree 2
  - The initial control points are $\mathbf{p}_i^0$ but are written $\mathbf{p}_i$

- Pronounced *beh-zee-eh*

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Bézier Curve

- Note:
  - Curve lies within the convex hull of the control points
  - Curve only passes through $\mathbf{p}_0$ and $\mathbf{p}_n$

Bézier Curve

- Repeated interpolation is cumbersome
  - Also inefficient for large n
- Can we do better?

Bézier Curve

- Repeated interpolation is cumbersome
  - Also inefficient for large n
- Can we do better?
  - Yes!
  - We can use *algebra* instead of interpolation

Bézier Basis Functions

- Rewrite a weighted sum of control points:

$$\mathbf{p}(t) = \sum_{i=0}^{n} \mathrm{B}_i^n(t)\,\mathbf{p}_i$$

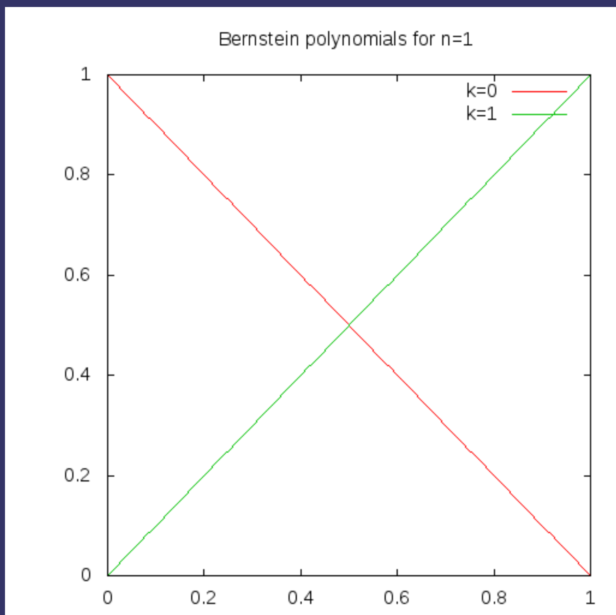
$$\begin{aligned} \mathrm{B}_i^n(t) &= \binom{n}{i} t^i (1-t)^{n-i} \\ &= \frac{n!}{i!(n-i)!} t^i (1-t)^{n-i} \end{aligned}$$

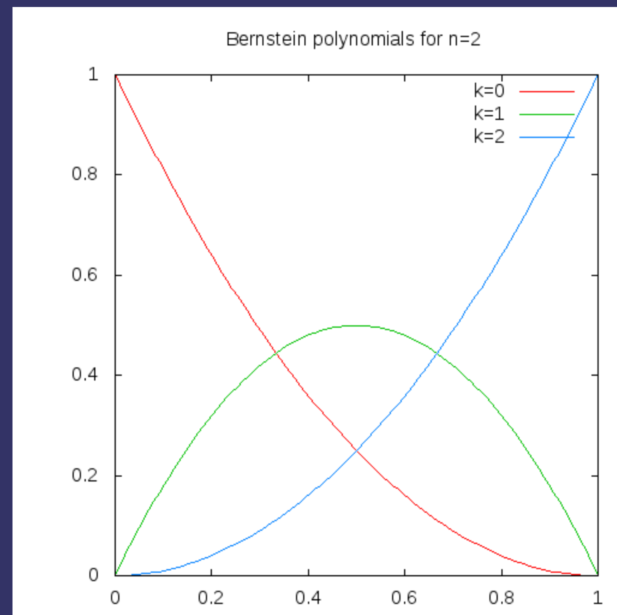
  - B_i^n is the *Bernstein polynomial* or *Bézier basis function*
  - Note:

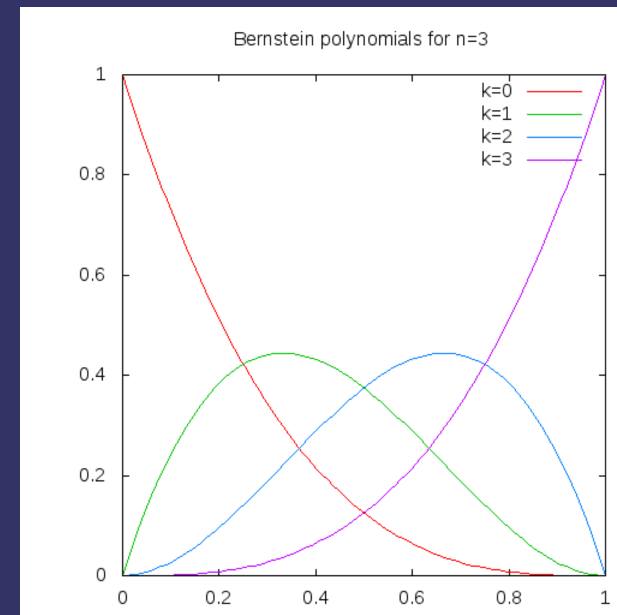
$$t \in [0,1] \rightarrow B_i^n(t) \in [0,1]$$

$$\sum_{i=0}^{n} B_i^n(t) = 1$$

Bézier Basis Functions







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Bézier Curve

- Usually unnecessary to go higher than n=3
  - Why?
    - What can a cubic polynomial do that a quadratic cannot?

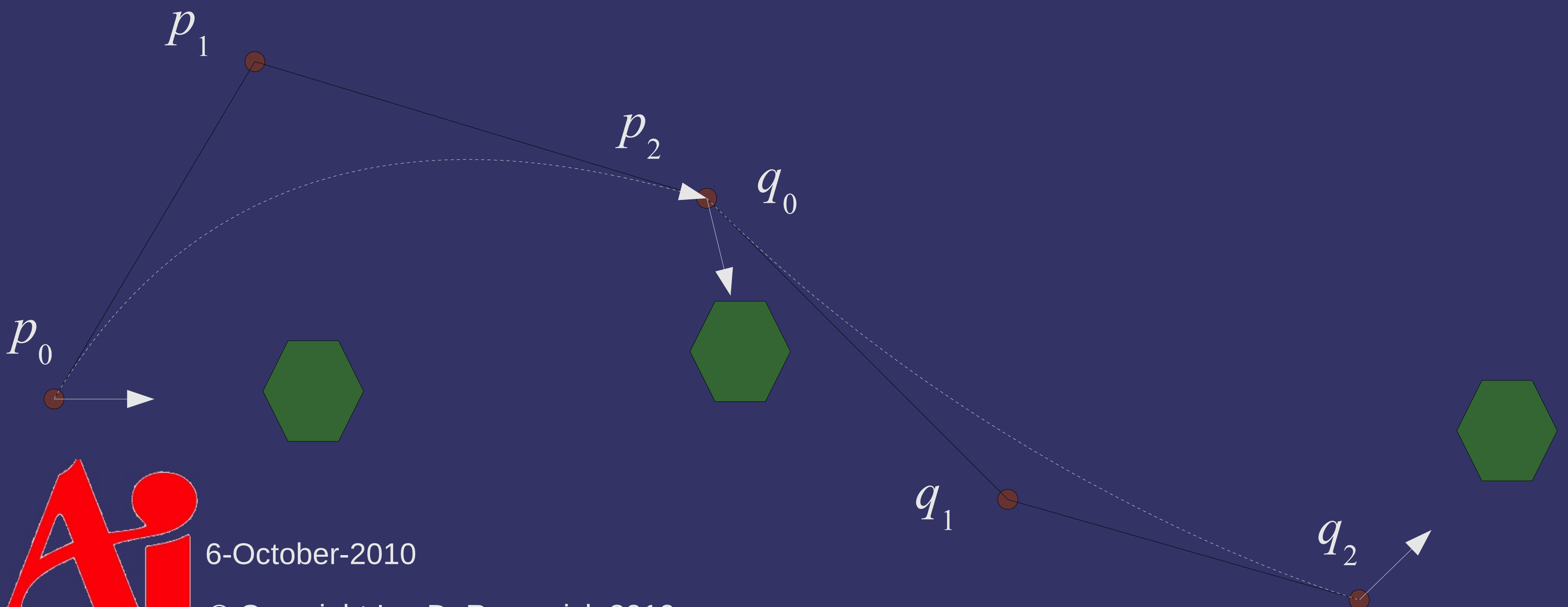
Bézier Curve

- Usually unnecessary to go higher than n=3
  - Why?
    - What can a cubic polynomial do that a quadratic cannot?
  - Cubic polynomials are the lowest degree whose derivative can change direction
    - Multiple cubic Bézier curves can be combined to approximate most shapes
  - Evaluation cost increases as n increases

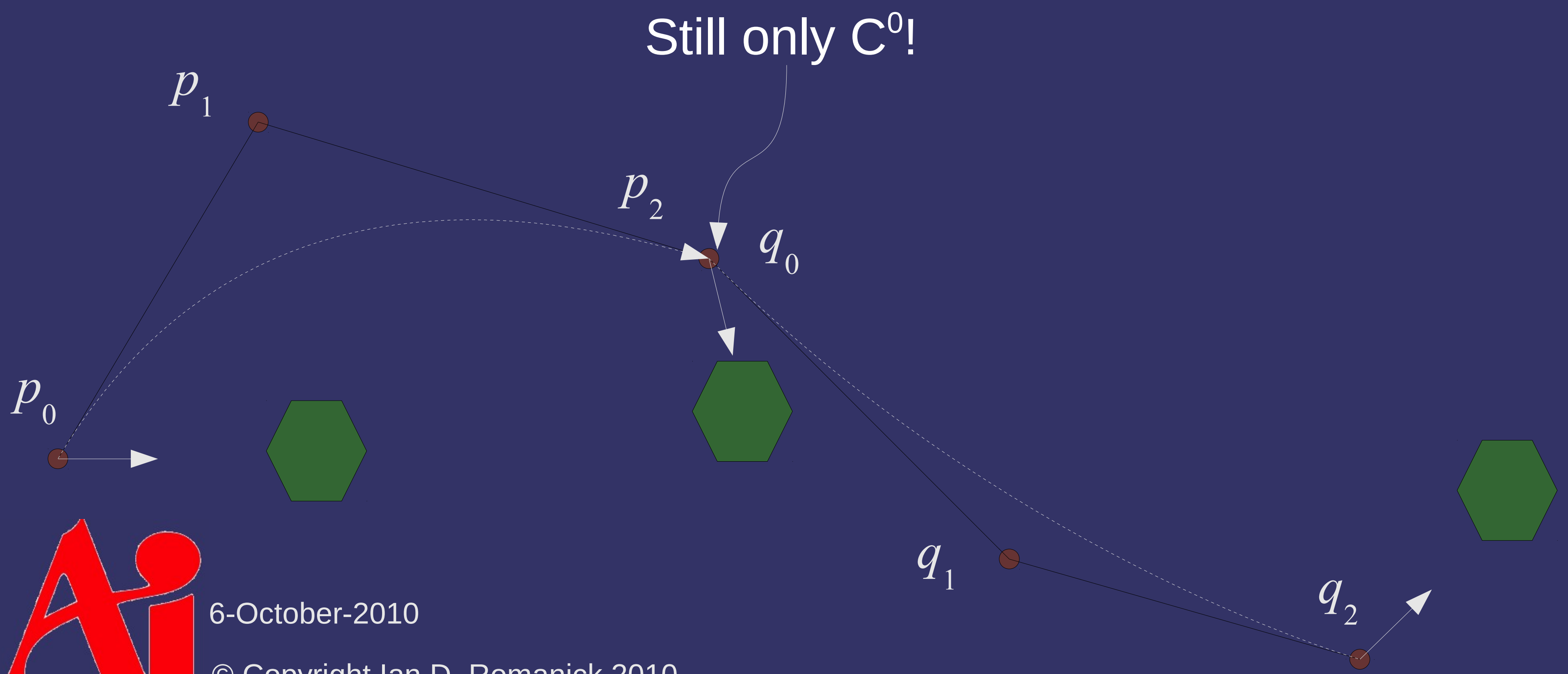
Piecewise Bézier Curves

- Curve only passes through $\mathbf{p}_0$ and $\mathbf{p}_n$
  - For camera control, we need to hit other definable points
- Define multiple curves
  - Control points $\mathbf{p}_i$, $\mathbf{q}_i$, $\mathbf{r}_i$, etc.
  - Set $\mathbf{p}_n = \mathbf{q}_0$
    - This is called a *joint*

Piecewise Bézier Curves



Piecewise Bézier Curves



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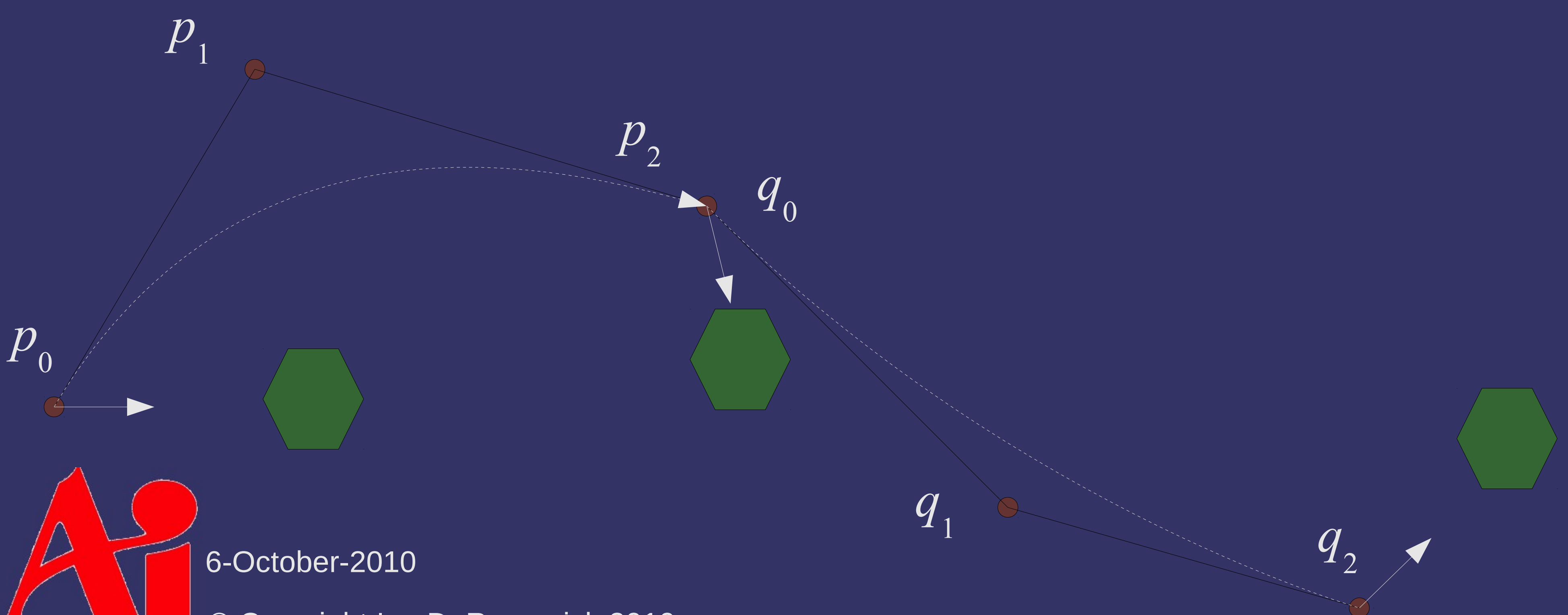
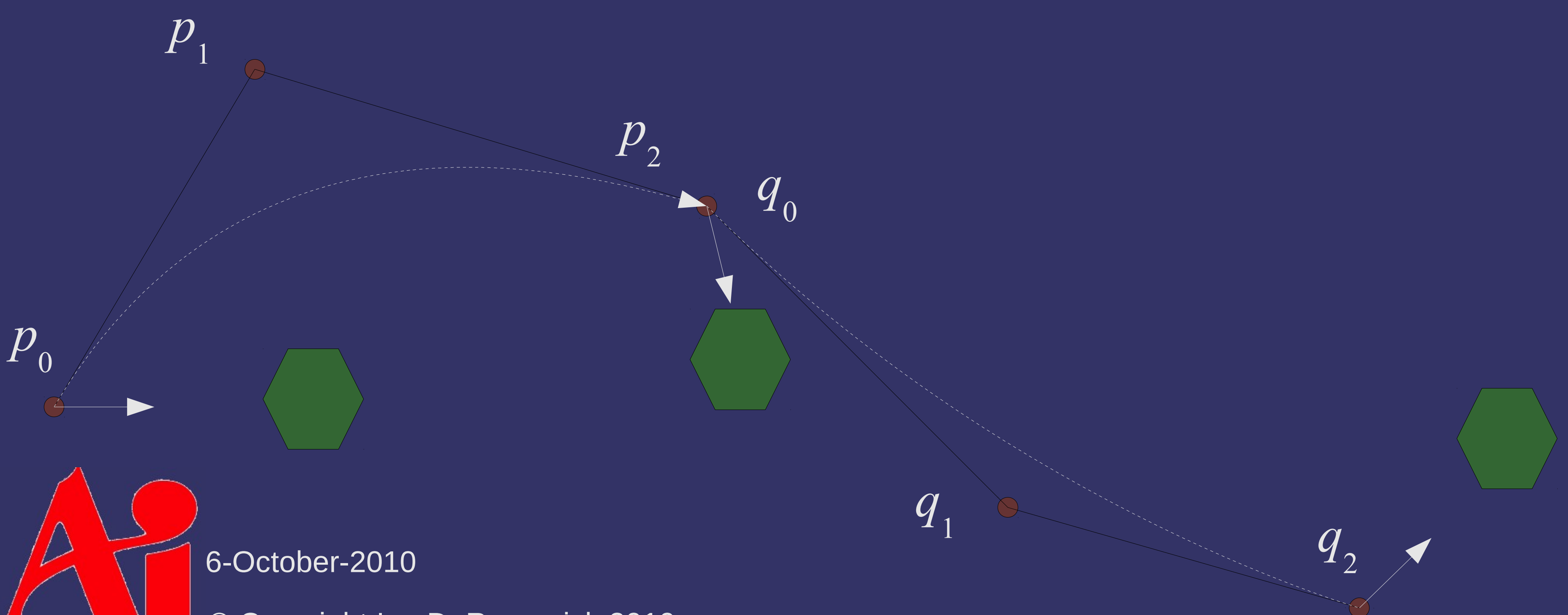
Piecewise Bézier Curves

- The piecewise function must be differentiable at the joint to be C^1
- What are the derivatives of $\mathbf{p}$ and $\mathbf{q}$ at the joint?



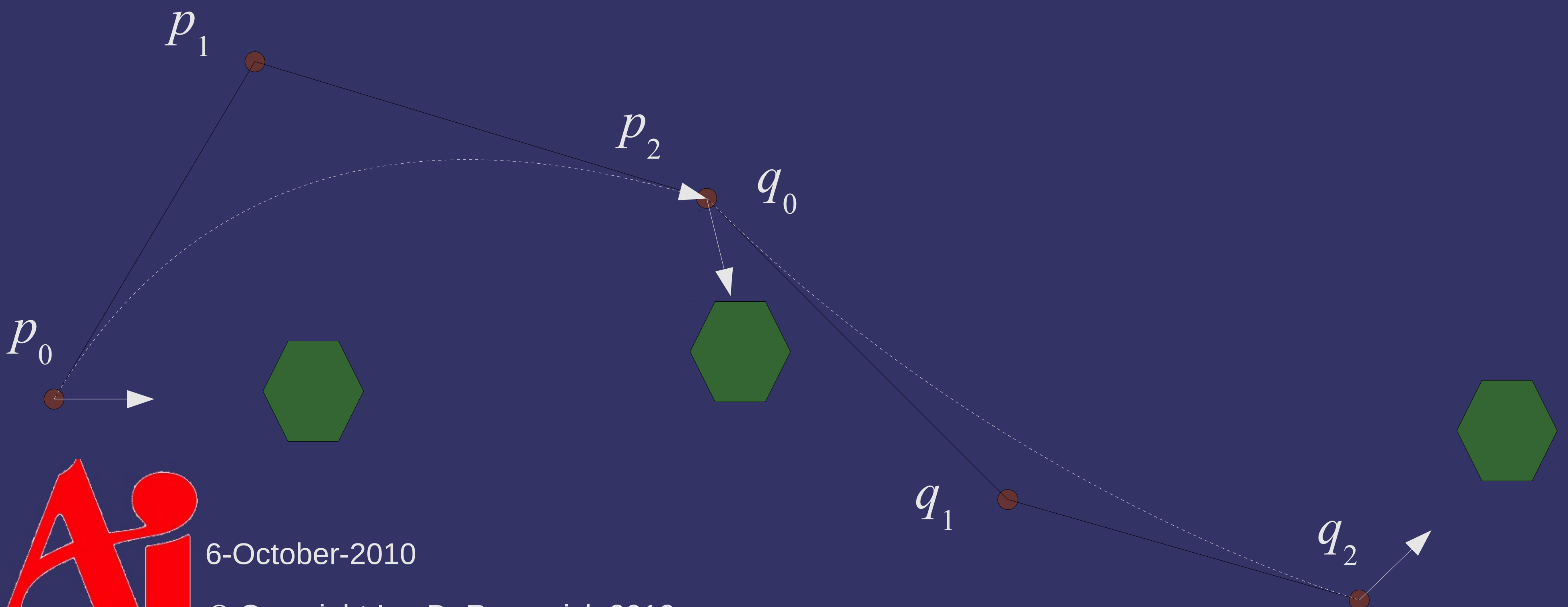
Piecewise Bézier Curves

- The piecewise function must be differentiable at the joint to be C^1
- What are the derivatives of $\mathbf{p}$ and $\mathbf{q}$ at the joint?
  - $\mathbf{p}'(1) = \mathbf{q}'(0)$



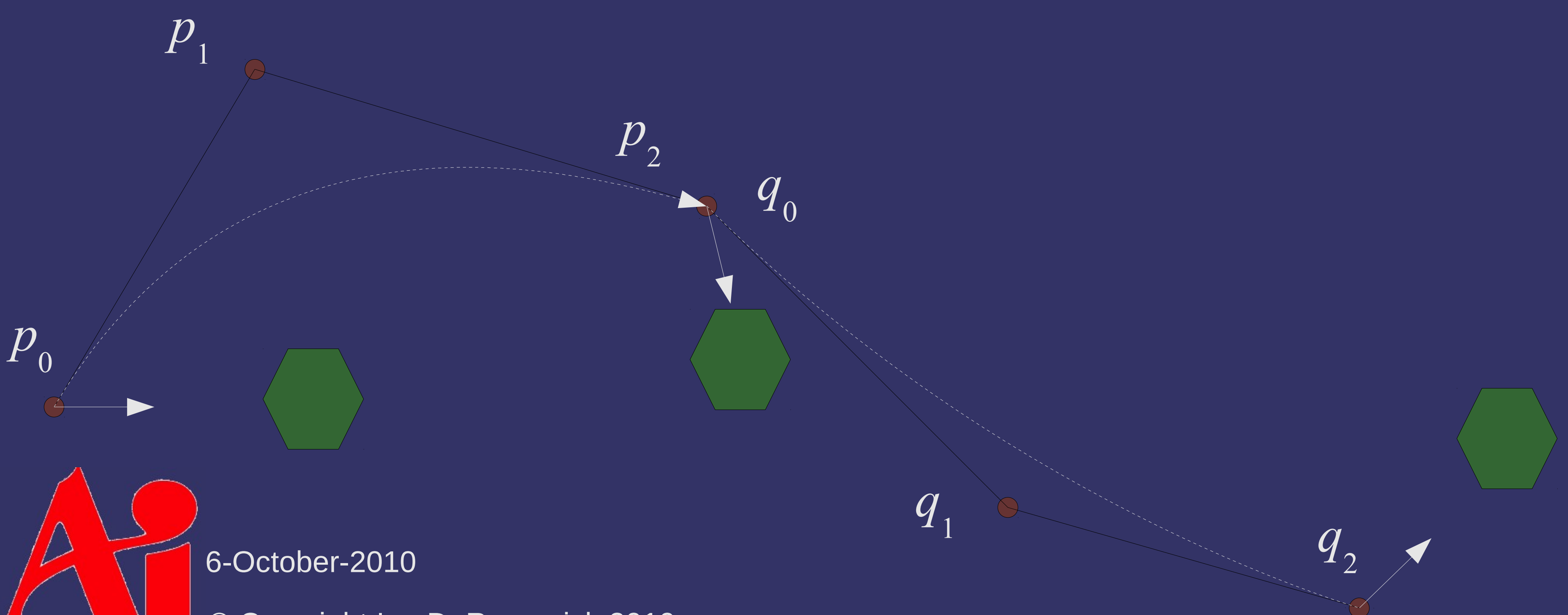
Piecewise Bézier Curves

- Generally, what is the value of the derivative of $\mathbf{f}$ at x?



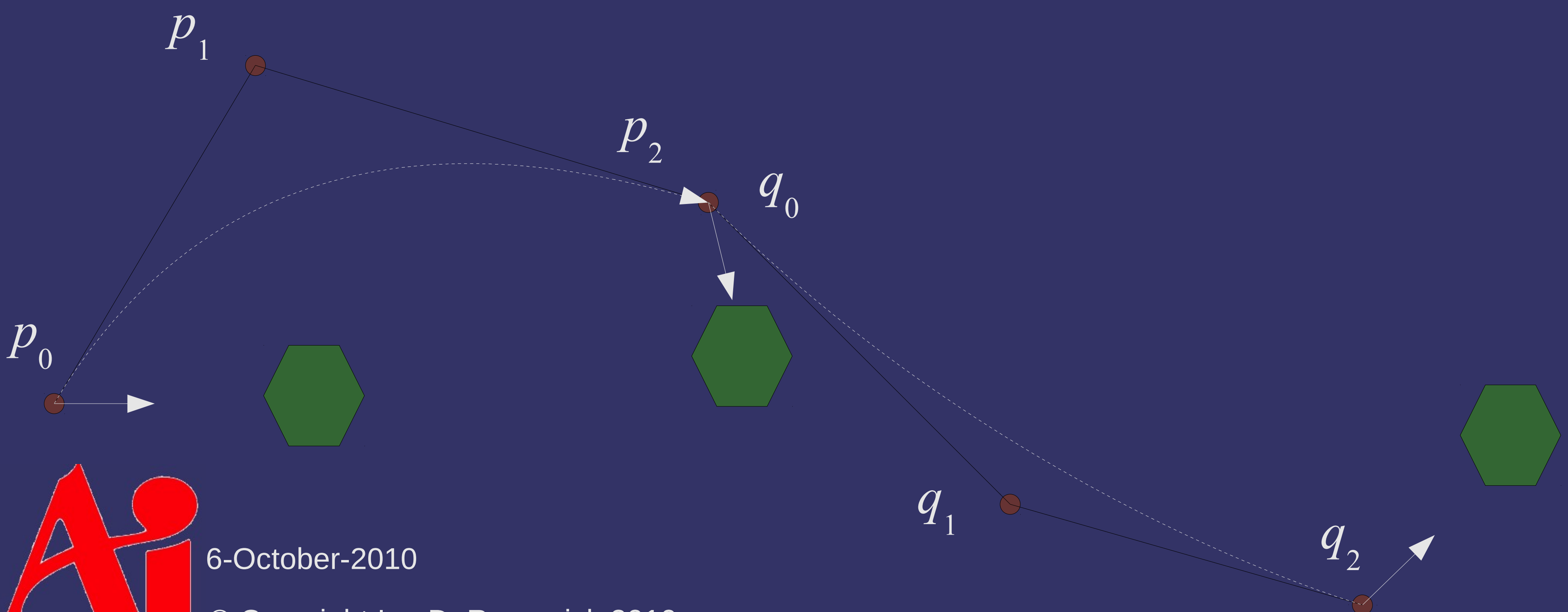
Piecewise Bézier Curves

- Generally, what is the value of the derivative of $\mathbf{f}$ at x?
  - The slope of a line *tangent* to $\mathbf{f}$ at x



Piecewise Bézier Curves

- What line is tangent to $\mathbf{p}$ at p_2?



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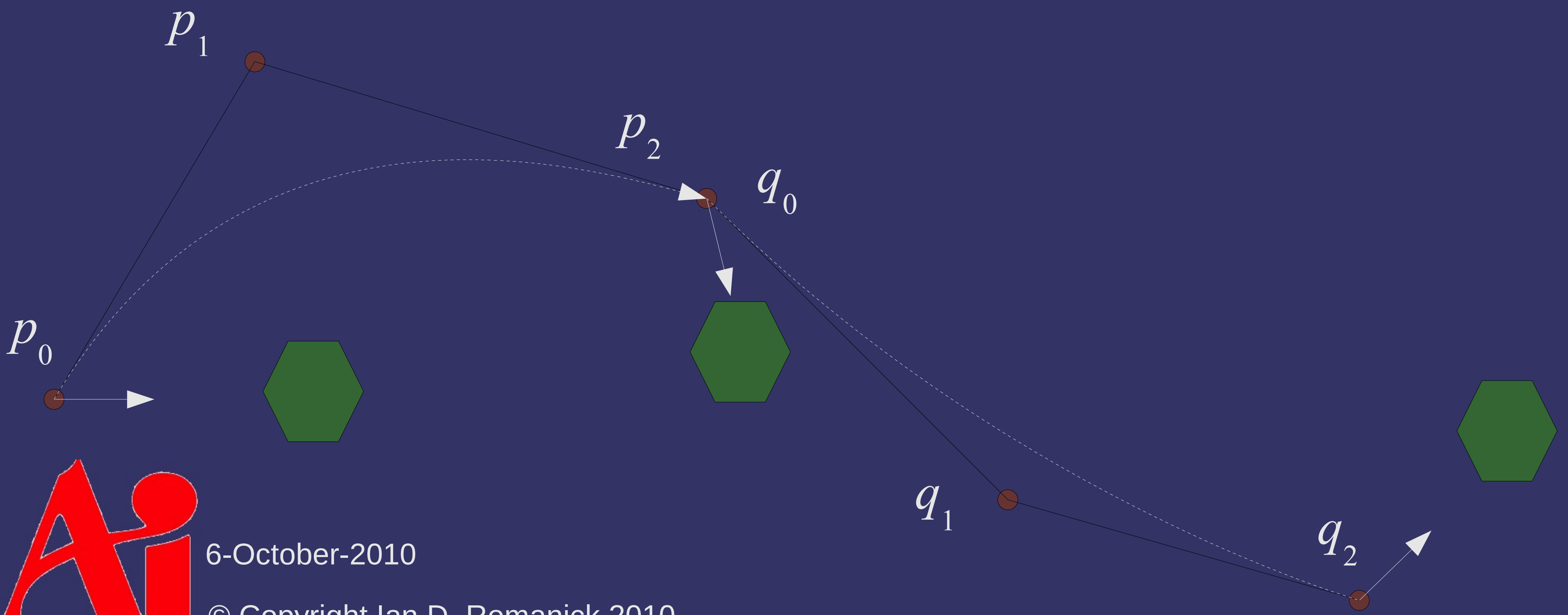
Piecewise Bézier Curves

- What line is tangent to $\mathbf{p}$ at p_2?
  - $\overline{p_1 p_2}$



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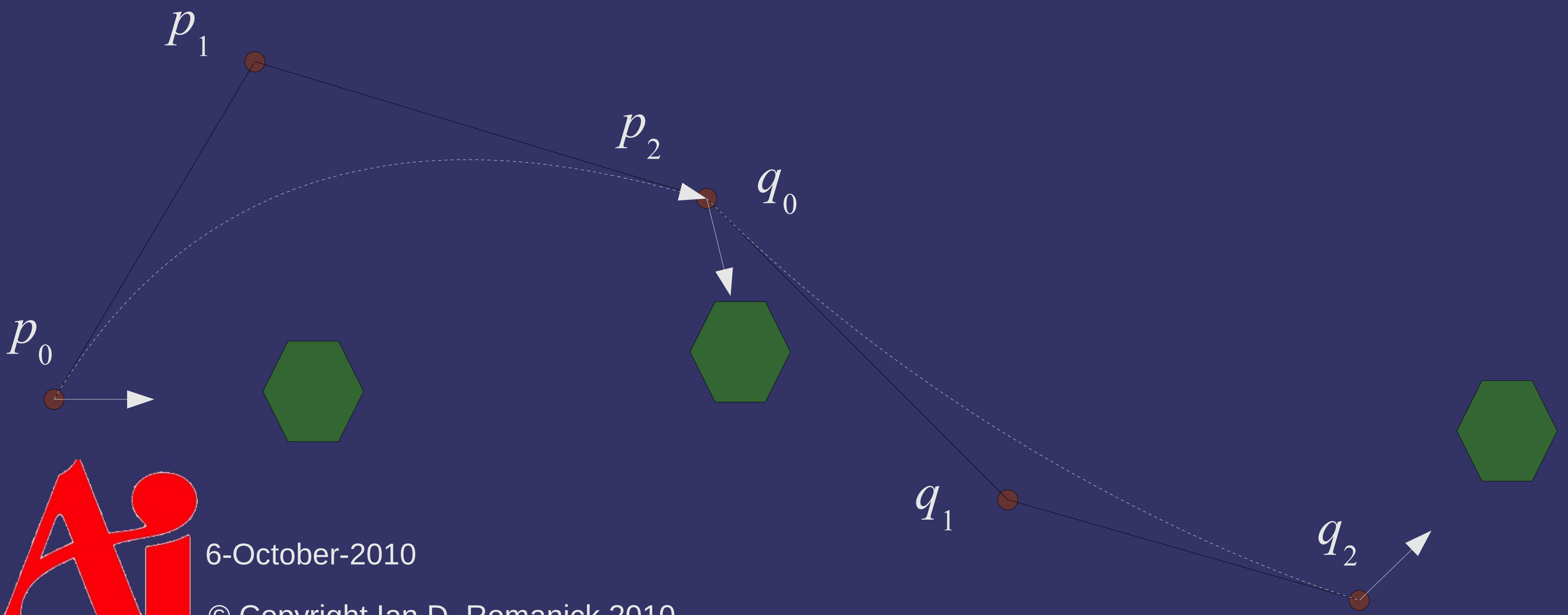
Piecewise Bézier Curves

- How can we achieve C^1?



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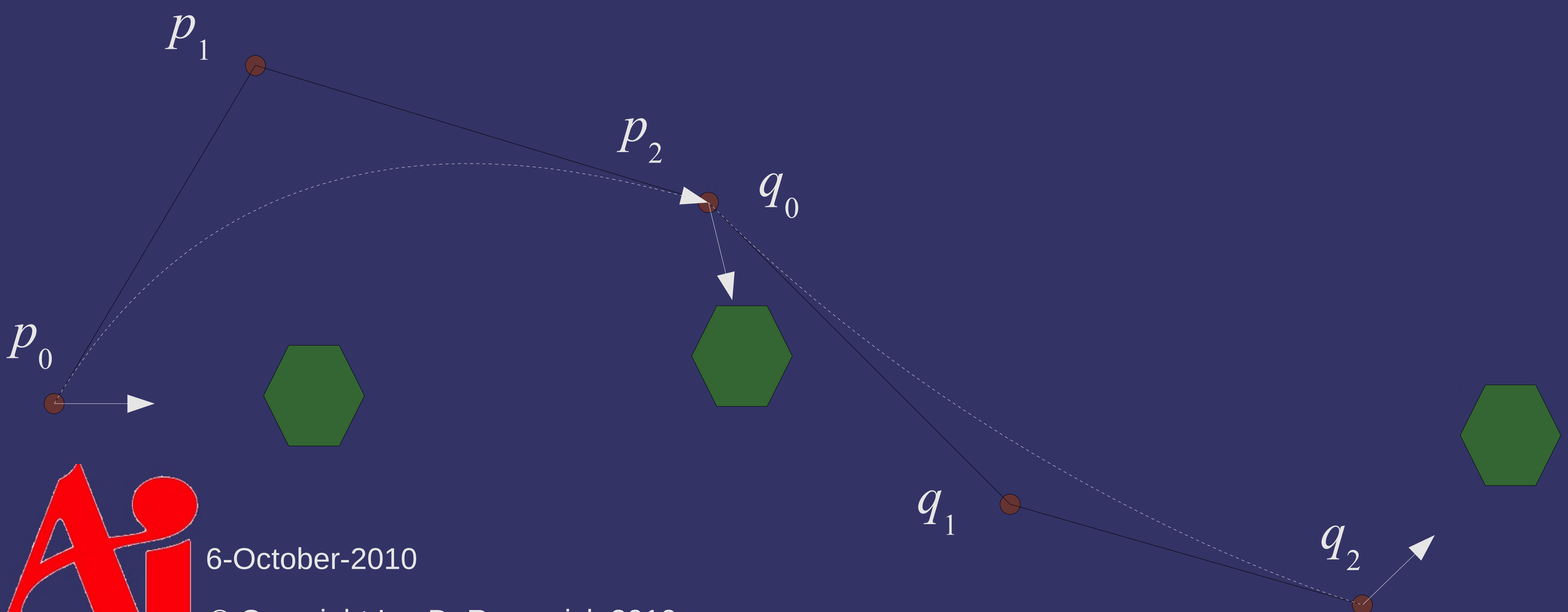
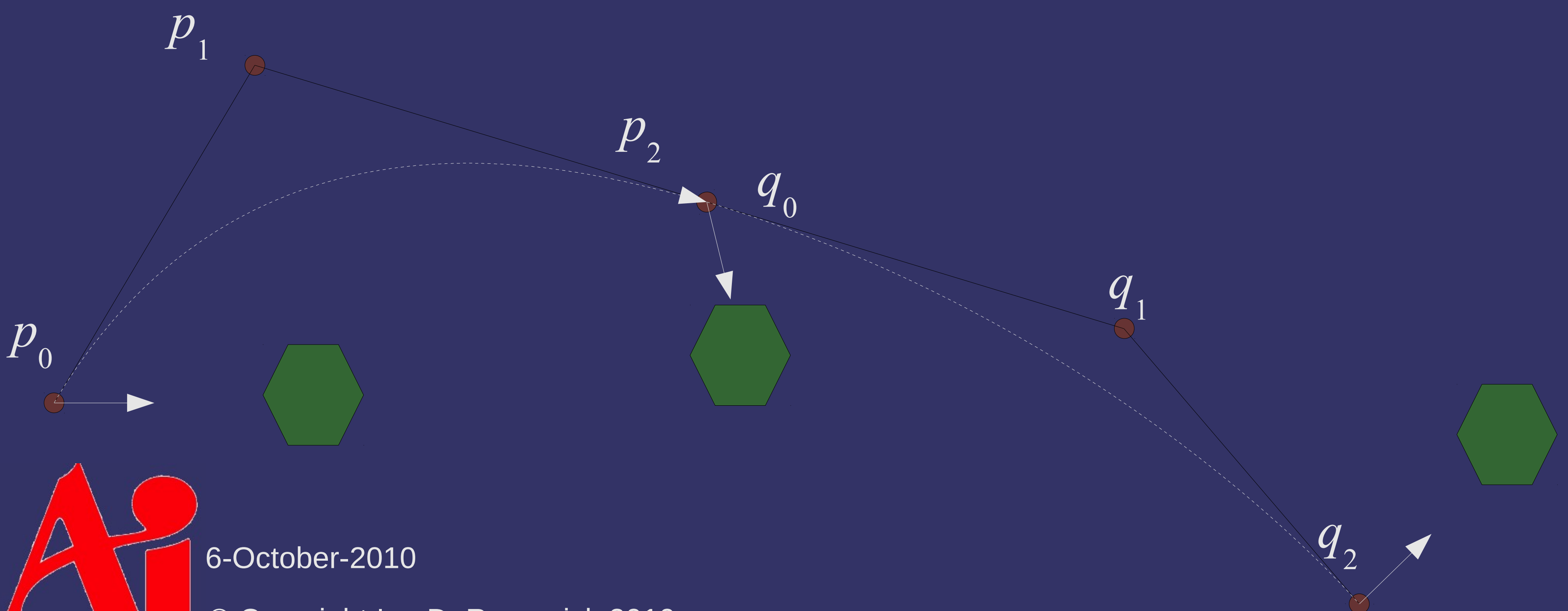
Piecewise Bézier Curves

- How can we achieve C^1?
  - Move p_1 and / or q_1 so that $\overline{p_1 p_2}$ and $\overline{q_0 q_1}$ are parallel



Piecewise Bézier Curves

- How can we achieve C[1]?
  - Move p_1 and / or q_1 so that $\overline{p_1 p_2}$ and $\overline{q_0 q_1}$ are parallel
  - This can dramatically change the curves



Piecewise Bézier Curves

- If $|\mathbf{m}_1| \neq |\mathbf{m}_2|$ there will be a speed change at the joint
  - This is *not* C^1, but it's better than C^0
  - Sometimes G^1 for *geometrical continuity*

Derivative of a Bézier Curve

- Derivative using the sum rule and regrouping:

$$\frac{d}{dt}\mathbf{p}(t) = n\sum_{i=0}^{n-1} B_i^{n-1}(t)(\mathbf{p}_{i+1} - \mathbf{p}_i)$$

  - Exercise for the reader to confirm:

$$\frac{d}{dt}\mathbf{p}(0) = \mathbf{p}_1 - \mathbf{p}_0$$

$$\frac{d}{dt}\mathbf{p}(1) = \mathbf{p}_n - \mathbf{p}_{n-1}$$

  - Result is a Bézier curve of one lower degree

Curved Surfaces

- Start with the same interpolation games
  - First extend from one parameter, t, to two parameters $\langle u, v\rangle$
  - Use four control points, $\mathbf{p}_{00}$, $\mathbf{p}_{01}$, $\mathbf{p}_{10}$, $\mathbf{p}_{11}$, instead of two
  - Interpolate between adjacent pairs:

$$\begin{aligned}
\mathbf{e} &= (1-u)\mathbf{p}_{00}+v\,\mathbf{p}_{01}\\
\mathbf{f} &= (1-u)\mathbf{p}_{10}+v\,\mathbf{p}_{11}\\
\mathbf{p}(u,v) &= (1-v)\mathbf{e}+v\,\mathbf{f}\\
&= (1-u)(1-v)\mathbf{p}_{00}+u(1-v)\mathbf{p}_{01}+(1-u)v\,\mathbf{p}_{10}+uv\,\mathbf{p}_{11}
\end{aligned}$$

  - Also known as *bilinear interpolation*

Curved Surfaces

- Extend to a curved surface in the same way as extending a line to a curve:
  - Add control points
    - For an $n \times m$ degree patch, there are $(n+1)(m+1)$ control points
    - Usually $n = m$
  - Recursively interpolate between the control points
    - Or use Bernstein form

Bézier Patches

- Bernstein form:

$$\mathbf{p}(u,v) = \sum_{i=0}^{m} \mathrm{B}_i^m(u) \sum_{j=0}^{n} \mathrm{B}_j^n(v)\, \mathbf{p}_{i,j}$$

  - As with Bézier curves:
    - Surface lies within convex hull of control points
    - And:

$$(u,v) \in [0,1] \times [0,1] \rightarrow B_i^m(u) B_j^n(v) \in [0,1]$$

$$\sum_{i=0}^{m} \sum_{j=0}^{n} B_i^m(u) B_j^n(v) = 1$$

    - Second summation is just a Bézier curve!

Bézier Patches

- Bernstein form:

$$\mathbf{p}(u,v)=\sum_{i=0}^{m}\mathrm{B}_i^m(u)\boxed{\sum_{j=0}^{n}\mathrm{B}_j^n(v)\,\mathbf{p}_{i,j}}$$

  – As with Bézier curves:
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$$(u,v)\in[0,1]\times[0,1]\rightarrow B_i^m(u)\,B_j^n(v)\in[0,1]$$

$$\sum_{i=0}^{m}\sum_{j=0}^{n}B_i^m(u)\,B_j^n(v)=1$$

    – Second summation is just a $\boxed{\text{Bézier curve!}}$

Derivative of a Bézier Patch

- Similar to Bézier curves:

$$\frac{\partial \mathbf{p}(u,v)}{\partial u} = m \sum_{j=0}^{n} \sum_{i=0}^{m-1} B_i^{m-1}(u) B_j^n(v) [\mathbf{p}_{i+1,j} - \mathbf{p}_{i,j}]$$

$$\frac{\partial \mathbf{p}(u,v)}{\partial v} = n \sum_{i=0}^{m} \sum_{j=0}^{n-1} B_i^m(u) B_j^{n-1}(v) [\mathbf{p}_{i,j+1} - \mathbf{p}_{i,j}]$$

Normals of a Bézier Patch

- How do we calculate the normal?
  - What we *really* want is the normal of the plane tangent to the surface

Normals of a Bézier Patch

- How do we calculate the normal?
  - What we *really* want is the normal of the plane tangent to the surface
  - The partial derivatives give two vectors that lie in that plane... just take the cross product!

$$\mathbf{n}(u,v) = \frac{\partial \mathbf{p}(u,v)}{\partial u} \times \frac{\partial \mathbf{p}(u,v)}{\partial v}$$

Phong Shading Recap

- Phong shading... aka per-fragment lighting
  - Calculate lighting parameters per-vertex
  - Interpolate calculated values
  - Calculate lighting per-fragment based on interpolated parameter values

Phong Shading Recap

```
attribute vec3 normal;
uniform mat3 normal_xform;
uniform mat4 vertex_xform;
uniform mat4 mvp;

varying vec3 normal_es;
varying vec3 pos_es;

void main(void)
{
    gl_Position = mvp * gl_Vertex;

    normal_es = normal_xform * normal;
    pos_es = vertex_xform * gl_Vertex;
}
```

Phong Shading Recap

```
uniform vec3 light_pos_es;
uniform vec4 diff_color;
varying vec3 normal_es;
varying vec3 pos_es;
const vec3 eye_es = vec3(0);

void main(void)
{
    vec3 l = normalize(light_pos_es – pos_es);
    vec3 v = normalize(eye_es - pos_es);
    vec3 h = normalize(l + v);
    float n_dot_l = dot(normal_es, l);
    vec4 diff = diff_color * n_dot_l;
    float spec = pow(dot(n, h), 16.0);

    gl_FragColor = step(0.0, n_dot_l) *
        vec4(diff.xyz + vec3(spec), 1.0);
}
```

Surface-Space

- From the point of view of the surface, what is the normal vector?
  - We'll call this *surface-space*

Surface-Space

- From the point of view of the surface, what is the normal vector?
  - We'll call this *surface-space*
  - Assuming the surface is flat, $\mathbf{n}_{surf} = (0, 0, 1)$

Surface-Space

- If we know $\mathbf{n}_{world}$, can we create transformation that will generate $\mathbf{n}_{surf}$?
  - Not uniquely
    - An orthonormal basis requires three orthogonal, normalized vectors, but we only have one
      - If we have two we can generate the third
    - This is the same reason we need the “up” vector to create the camera look-at transform
  - If only we had another vector in plane...

Surface-Space

- Create a new vector, and call it the *tangent*
  - Either partial derivative of a Bézier patch can be used for $\mathbf{t}_{surf}$
    - Usually $\partial\mathbf{p}/\partial u$ is used
  - Knowing $\mathbf{n}_{surf}$ and $\mathbf{t}_{surf}$ is enough to create an orthonormal basis
  - This basis can transform *any* vector to surface-space from object-space
    - $\mathbf{n}_{obj}$ is an obvious choice
    - For lighting, $\mathbf{v}$ and $\mathbf{l}$ need to be in the same space as $\mathbf{n}$
- Because the tangent vector is used, surface-space is sometimes called *tangent-space*

Surface-Space

```
varying vec3 light_ss;
varying vec3 eye_ss;
attribute vec3 tangent;
attribute vec3 normal;

void main(void)
{
    gl_Position = mvp * gl_Vertex;

    vec3 tangent_es = normal_xform * tangent;
    vec3 normal_es = normal_xform * normal;
    vec3 bitangent_es = cross(normal_es, tangent_es);
    mat3 tbn = mat3(tangent_es, bitangent_es, normal_es);

    vec3 pos_es = vec3(vertex_xform * gl_Vertex);
    vec3 light_es = light_pos_es - pos_es;

    light_ss = normalize(light_es * tbn);
    eye_ss = -normalize(pos_es * tbn);
}
```

Surface-Space

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varying vec3 light_ss;
varying vec3 eye_ss;
attribute vec3 tangent;
attribute vec3 normal;

void main(void)
{
    gl_Position = mvp * gl_Vertex;

    vec3 tangent_es = normal_xform * tangent;
    vec3 normal_es = normal_xform * normal;
    vec3 bitangent_es = cross(normal_es, tangent_es);
    mat3 tbn = mat3(tangent_es, bitangent_es, normal_es);

    vec3 pos_es = vec3(vertex_xform * gl_Vertex);
    vec3 light_es = light_pos_es - pos_es;

    light_ss = normalize(light_es * tbn);
    eye_ss = -normalize(pos_ss * tbn);
}
```

This actually calculates $\mathbf{M}_s^T$

Surface-Space

```
varying vec3 light_ss;
varying vec3 eye_ss;
attribute vec3 tangent;
attribute vec3 normal;

void main(void)
{
    gl_Position = mvp * gl_Vertex;

    vec3 tangent_es = normal_xform * tangent;
    vec3 normal_es = normal_xform * normal;
    vec3 bitangent_es = cross(normal_es, tangent_es);
    mat3 tbn = mat3(tangent_es, bitangent_es, normal_es);

    vec3 pos_es = vec3(vertex_xform * gl_Vertex);
    vec3 light_es = light_pos_es - pos_es;

    light_ss = normalize(light_es * tbn);
    eye_ss = -normalize(pos_ss * tbn);
}
```

This actually calculates $\mathbf{M}_s^T$

Remember: $\mathbf{Mv} = \mathbf{vM}^T$

Surface-Space

```
varying vec3 light_ss;
varying vec3 eye_ss;
uniform vec4 diff_color;

void main(void)
{
    vec3 l = normalize(light_ss);
    vec3 v = normalize(eye_ss);
    vec3 h = normalize(l + v);
    float n_dot_l = l.z;
    vec4 diff = diff_color * n_dot_l;
    float spec = pow(h.z, 16.0);

    gl_FragColor = step(0.0, n_dot_l) *
        vec4(diff.xyz + vec3(spec), 1.0);
}
```

Surface-Space

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varying vec3 light_ss;
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        vec4(diff.xyz + vec3(spec), 1.0);
}
```

Remember: **n** is (0, 0, 1)!

Surface-Space

- What is $\mathbf{b}$?
  - In the calculation: $\mathbf{b} = \mathbf{n} \times \mathbf{t}$
  - Correctly, this is the *bi-tangent*
    - Many places incorrectly call it the bi-normal
    - Either way, we'll just call it $\mathbf{b}$
  - Generally easier and more efficient to compute this in a shader than supply it as an input
    - We *cannot* just use $\partial\mathbf{p}/\partial v$ from from our surface evaluation because the two partial derivatives may not be orthogonal to each other!

Surface-Space

- What does this math headache gain us?
  - Just a trivial fragment shader optimization so far
    - Seems hardly worth it
  - What else?

Bump Mapping

- What if the surface isn't really flat or smoothly curved?
  - Just like few real surfaces have truly uniform color, few real surfaces have uniform normals
  - Use the same solution!
    - Store colors in an image → store normals in an image

Normal Map Storage

- Store the X, Y, and Z values of the surface-space normals in the R, G, and B components
  - Since Z tends to be close to 1.0, these images tend to look very blue

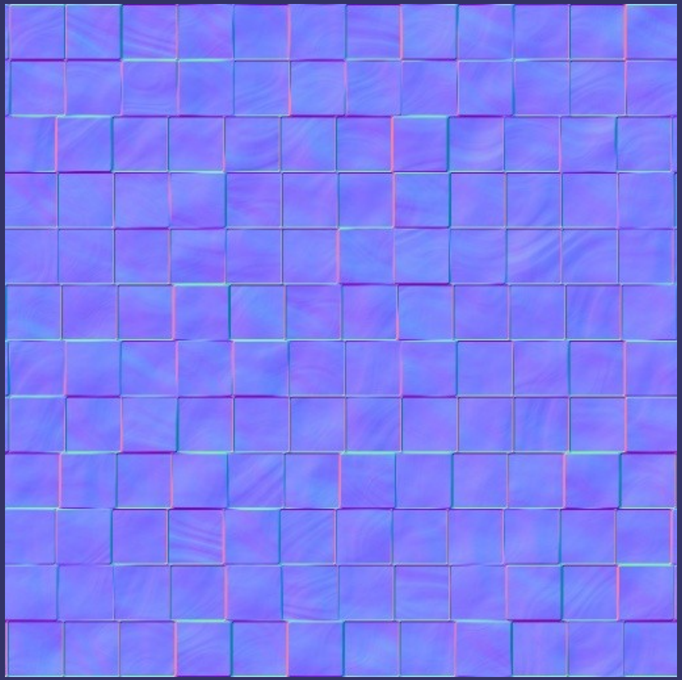

Image from http://www.filterforge.com/filters/243-normal.html

Normal Map Storage

- What is the range of colors in a texture?

Normal Map Storage

- What is the range of colors in a texture?
  - [0.0, 1.0]
  - We have to convert these to the [-1, 1] range desired for normal directions
    - Just convert X and Y... Z must be > 0, so just leave it

Normal Map Storage

- We don't even need Z
  - Z must always be > 0.0
  - Derive it from X and Y:

Normal Map Storage

- We don't even need Z
  - Z must always be > 0.0
  - Derive it from X and Y:

$$\sqrt{x^2+y^2+z^2}=1.0$$
$$x^2+y^2+z^2=1.0$$
$$z^2=1.0-x^2-y^2$$
$$z=\sqrt{1.0-x^2-y^2}$$

Normal Map Storage

- 2-component textures can be achieved in a couple ways:
  - Use `GL_LUMINANCE_ALPHA`
    - Some hardware doesn't really support this, so it will silently convert it to RGBA...making it bigger
  - Use `GL_RG`
    - Requires `GL_ARB_texture_rg` or OpenGL 3.0
  - Use `GL_COMPRESSED_RED_GREEN_RGTC2_EXT`
    - Requires `GL_ARB_texture_compression_rgtc`, `GL_EXT_texture_compression_rgtc`, or OpenGL 3.0
    - May add undesired compression artifacts

References

Lengyel, Eric. “Computing Tangent Space Basis Vectors for an Arbitrary Mesh”. Terathon Software 3D Graphics Library, 2001. http://www.terathon.com/code/tangent.html

Normal map photography tutorial:

http://www.zarria.net/nrmphoto/nrmphoto.html

OpenGL extension specs:

http://www.opengl.org/registry/specs/ARB/texture_rg.txt

http://www.opengl.org/registry/specs/ARB/texture_compression_rgtc.txt

Next week...

- Render-to-texture
- Environment mapping
  - Rendering to env maps
- Improving the reflection model
  - Using env maps as better lights
  - Fresnel reflection
- Read:

Michael Toksvig. “Mipmapping Normal Maps.” http://developer.nvidia.com/object/mipmapping_normal_maps.html

Real-Time Rendering 3rd Edition, chapter 13.1 and 13.2.

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