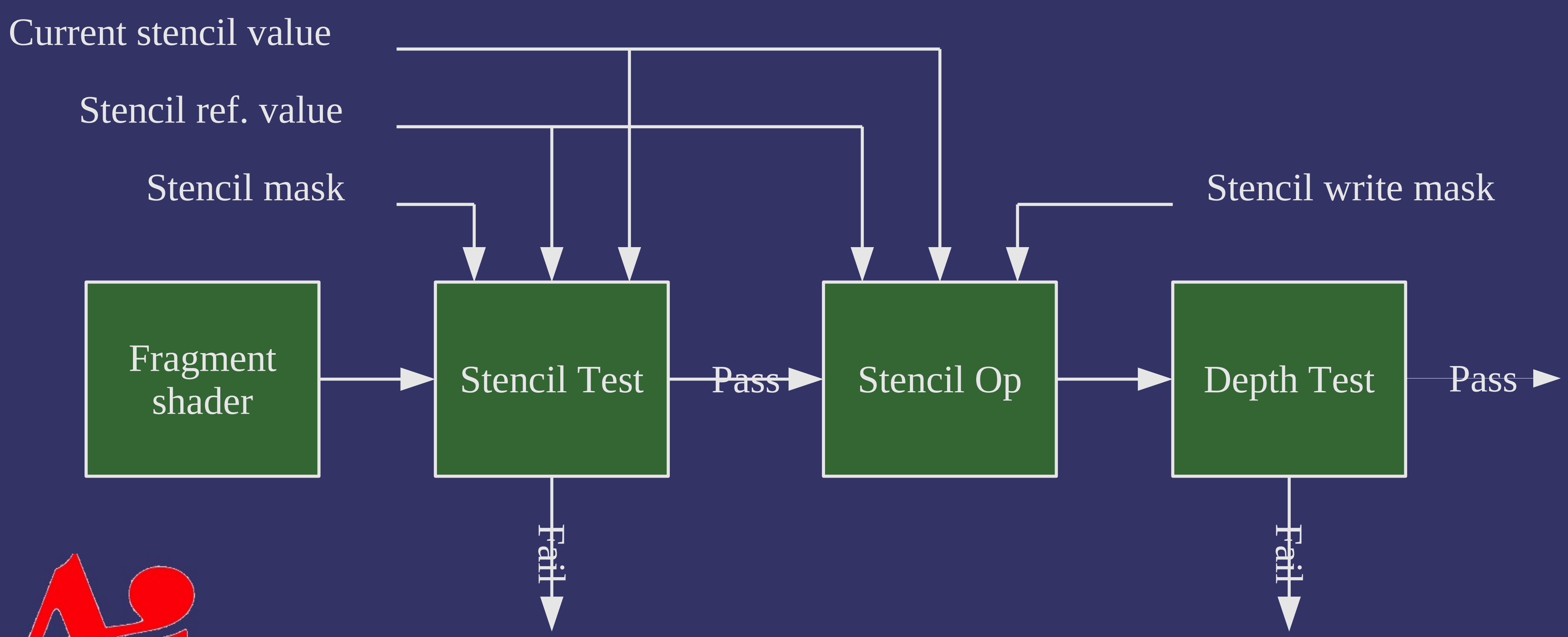
VGP353 – Week 5

- Agenda:
  - Quiz #2
  - Stencil-buffer refresher
  - Theory of shadow volumes
  - Generating shadow volume geometry

Stencil Buffer

- Extra per-pixel buffer containing integer values
  - Stencil test and stencil operation occur *after* per-fragment operations and *before* depth testing



Stencil Buffer

- Stencil function is one GL's usual comparators
  - `GL_NEVER`, `GL_LESS`, `GL_EQUAL`, `GL_LEQUAL`, `GL_GREATER`, `GL_NOTEQUAL`, `GL_GEQUAL`, `GL_ALWAYS`
  - Performs bit-wise operations of `(stencil & mask) func (ref & mask)`

Stencil Buffer

```
glStencilFuncSeparate(
  GLenum face,
  GLenum func,
  GLint ref,
  GLuint mask);
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Stencil Buffer

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Polygon facing selector: different operations for front and back facing polygons

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Comparison function

Reference value used in comparison

Stencil Buffer

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- func: Comparison function
- ref: Reference value used in comparison
- mask: Bit-wise mask used on values before comparison

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- func: Comparison function
- ref: Reference value used in comparison
- mask: Bit-wise mask used on values before comparison

- Passing `GL_FRONT_AND_BACK` for `face` acts like GL 1.x `glStencilFunc` function
  - Radeon r300 (e.g., Radeon 9800) needs front and back `ref` and `mask` to be the same

Stencil Operation

- Stencil buffer values are modified per-fragment depending on the state of the fragment:
  - Fragment failed the stencil test
  - Fragment passed the stencil test but failed the depth test
  - Fragment passed the stencil test and passed the depth test

Stencil Operation

- Eight possible operations:
  - `GL_KEEP` – Keep existing value
  - `GL_ZERO` – Set value to zero
  - `GL_REPLACE` – Replace value with a reference value
  - `GL_INCR` – Increment value, clamp to max
    - `GL_INCR_WRAP` – Increment value, wrap to zero
  - `GL_DECR` – Decrement value, clamp to zero
    - `GL_DECR_WRAP` – Decrement value, wrap to max
  - `GL_INVERT` – Bitwise inversion of value
- Result is always masked with the stencil mask

Stencil Buffer

```
glStencilOpSeparate(
  GLenum face,
  GLenum sfail,
  GLenum dfail,
  GLenum dpass);
```

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Polygon facing selector: different operations for front and back facing polygons

Operation when stencil test fails

Stencil Buffer

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- dfail: Operation when stencil test passes but depth test fails

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- sfail: Operation when stencil test fails
- dfail: Operation when stencil test passes but depth test fails
- dpass: Operation when stencil and depth tests pass

Stencil Buffer

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glStencilOpSeparate(
    GLenum face,
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- `face`: Polygon facing selector: different operations for front and back facing polygons
- `sfail`: Operation when stencil test fails
- `dfail`: Operation when stencil test passes but depth test fails
- `dpass`: Operation when stencil and depth tests pass

- Passing `GL_FRONT_AND_BACK` for `face` acts like GL 1.x `glStencilOp` function

Stencil Buffer

- Stencil buffer can also be cleared
  - `glClearStencil` sets the cleared value
  - Pass `GL_STENCIL_BUFFER_BIT` to `glClear`
  - If depth *and* stencil are used, always clear both together

Stencil Buffer

- Writing of particular bits can be controlled with `glStencilMaskSeparate`
  - Passing `GL_FRONT_AND_BACK` for face parameter acts like GL 1.x `glStencilMask` function
  - Radeon r300 (e.g., Radeon 9800) needs front and back `mask` to be the same

Stencil Buffer – Example

```
glClearStencil(0);
glClear(GL_STENCIL_BUFFER_BIT);
glEnable(GL_STENCIL_TEST);

// Write 1 to stencil where polygon is drawn.
glStencilFuncSeparate(GL_FRONT_AND_BACK, GL_ALWAYS, 1, ~0);
glStencilOpSeparate(GL_FRONT_AND_BACK,
                    GL_KEEP, GL_KEEP, GL_REPLACE);
draw_some_polygon();

// Draw scene only where stencil buffer is 1.
glStencilFuncSeparate(GL_FRONT_AND_BACK, GL_EQUAL, 1, ~0);
glStencilOpSeparate(GL_FRONT_AND_BACK,
                    GL_KEEP, GL_KEEP, GL_KEEP);
draw_scene();
```

Stencil Buffer – Window System

- Stencil buffer is often stored interleaved with depth buffer
  - 8-bit stencil with 24-bit depth is most common
  - Other combinations such as 1-bit stencil with 15-bit depth do exist (very, *very* rare these days)
- Must request a stencil buffer with your window
  - With SDL, this means setting the stencil size attribute to the minimum number of stencil bits required

```
SDL_GL_SetAttribute(SDL_GL_STENCIL_SIZE, 4);
```

Stencil Buffer – FBOs

- Stencil buffers can also be used with framebuffer objects
  - Create with `glRenderbufferStorage` and an internal type of `GL_STENCIL_INDEX`
    - Sized types are also available
    - There are *no* stencil textures
  - Attach to `GL_STENCIL_ATTACHMENT`

Stencil Buffer – FBOs

- If depth *and* stencil are required:
  - Create renderbuffer *or* texture with internal type of `GL_DEPTH_STENCIL`
    - One sized type of `GL_DEPTH24_STENCIL8`
    - `type` parameter must be `GL_UNSIGNED_INT_24_8`
    - Treated as a depth texture for texturing
  - Bind same object to both the depth and stencil attachments
  - Added with OpenGL 3.0, `GL_ARB_framebuffer_objects`, or `GL_EXT_packed_depth_stencil`

Stencil Buffer – FBO Example

```
glGenFramebuffers(1, &fb);
glGenTextures(2, tex_names);

// Setup color texture (mipmap)
glBindTexture(GL_TEXTURE_2D, tex_names[0]);
glTexImage2D(GL_TEXTURE_2D, 0, GL_RGB8, 512, 512, 0, GL_RGBA, GL_INT, NULL);
glGenerateMipmap(GL_TEXTURE_2D);

// Setup depth_stencil texture (not mipmap)
glBindTexture(GL_TEXTURE_2D, tex_names[1]);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);
glTexImage2D(GL_TEXTURE_2D, 0, GL_DEPTH24_STENCIL8, 512, 512, 0,
             GL_DEPTH_STENCIL, GL_UNSIGNED_INT_24_8, NULL);

glBindFramebuffer(GL_FRAMEBUFFER_EXT, fb);
glFramebufferTexture2D(GL_FRAMEBUFFER, GL_COLOR_ATTACHMENT0,
                      GL_TEXTURE_2D, tex_names[0], 0);
glFramebufferTexture2D(GL_FRAMEBUFFER, GL_DEPTH_ATTACHMENT,
                       GL_TEXTURE_2D, tex_names[1], 0);
glFramebufferTexture2D(GL_FRAMEBUFFER, GL_STENCIL_ATTACHMENT,
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             GL_DEPTH_STENCIL, GL_UNSIGNED_INT_24_8, NULL);

glBindFramebuffer(GL_FRAMEBUFFER_EXT, fb);
glFramebufferTexture2D(GL_FRAMEBUFFER, GL_COLOR_ATTACHMENT0,
                       GL_TEXTURE_2D, tex_names[0], 0);
glFramebufferTexture2D(GL_FRAMEBUFFER, GL_DEPTH_ATTACHMENT,
                        GL_TEXTURE_2D, tex_names[1], 0);
glFramebufferTexture2D(GL_FRAMEBUFFER, GL_STENCIL_ATTACHMENT,
                        GL_TEXTURE_2D, tex_names[1], 0);
```

Same object attached both places

Shadow Volumes

- Proposed by Frank Crow in 1977
  - Add new geometry to the scene that describes the volume occluded from the light source
  - Objects within the volume are in shadow, objects not within the volume are not
  - Sometimes called *Crow shadows* or *Crow shadow volumes*

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  - Objects within the volume are in shadow, objects not within the volume are not
  - Sometimes called *Crow shadows* or *Crow shadow volumes*
- In 1991, Tim Heidmann showed how the stencil buffer can be used to apply these volumes to a scene
  - This adaptation often called *stencil volume shadows*

Shadow Volumes

- Basic algorithm:
  1. Render scene using only ambient light
  2. For each light in the scene:
     a. Using the depth information from the initial pass, construct a stencil with “holes” where there the light is not occluded.
        - Stencil will be 0 where the light is visible
     b. Render scene again with normal lighting. Use the stencil mask to only draw where the light is not occluded.
        - Configure stencil test to draw only where stencil = 0
- Two common methods to create this stencil: z-pass and z-fail

Shadow Volumes

- Problems?

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  - ***Very*** fill-rate intensive
  - Calculating shadow volumes can be complex and time consuming
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Shadow Volumes

- Problems?
  - ***Very*** fill-rate intensive
  - Calculating shadow volumes can be complex and time consuming
  - Difficult to extend to soft-shadows
- Advantages?
  - Since everything is done in geometry-space instead of image-space, **no aliasing artifacts!!!**
  - No shadow acne either!

Shadow Volumes – Z-Pass

1. Disable depth and color writes
2. Configure stencil operation:
   - `GL_INCR_WRAP` on depth pass front-faces
   - `GL_DECR_WRAP` on depth pass back-faces
   - `GL_KEEP` for all other cases
3. Draw shadow volumes

- Why use `GL_INCR_WRAP` and `GL_DECR_WRAP` instead of `GL_INCR` and `GL_DECR`?

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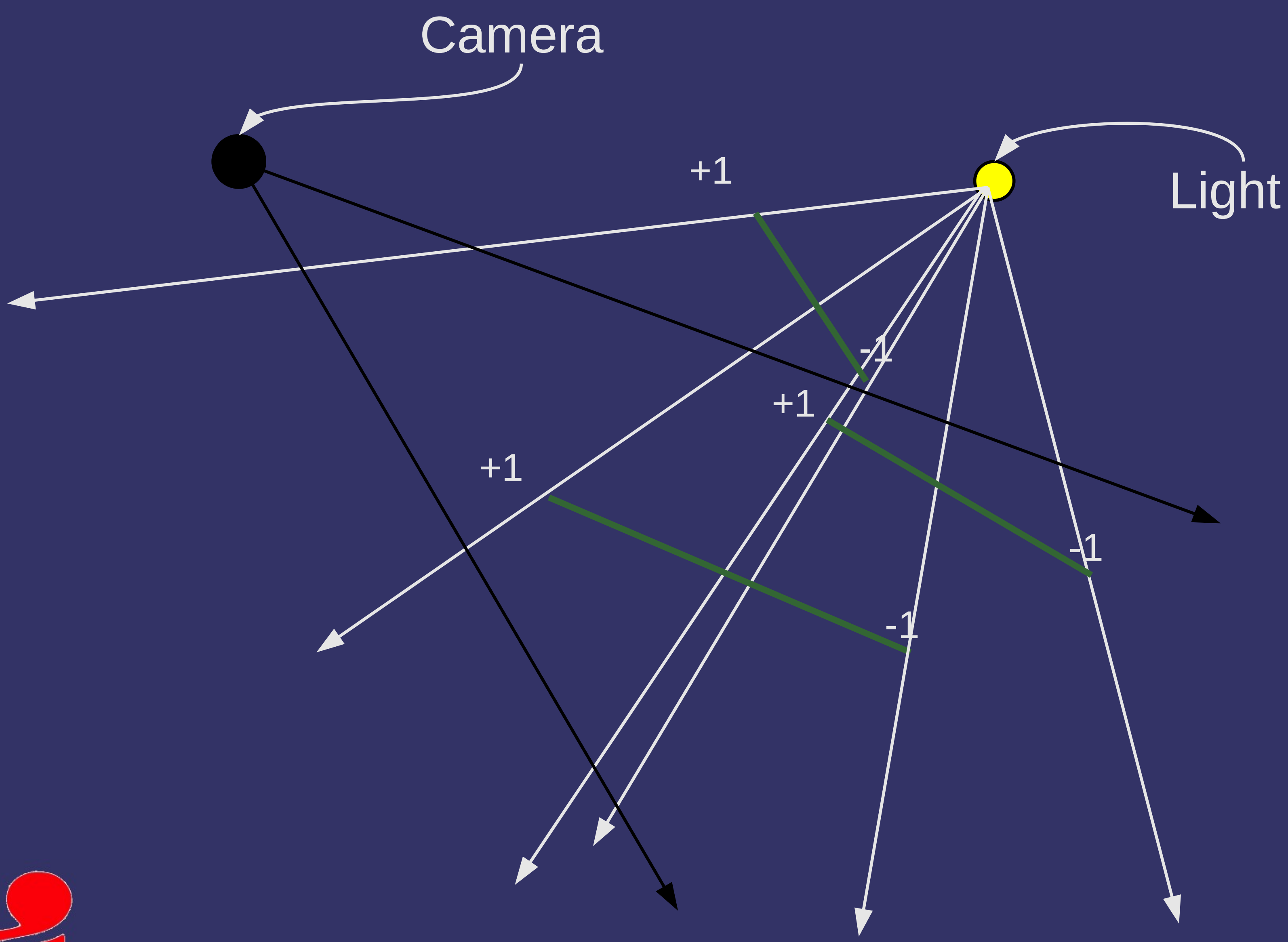
- Why use `GL_INCR_WRAP` and `GL_DECR_WRAP` instead of `GL_INCR` and `GL_DECR`?
  - Otherwise, if there are more than 2^n increments before a decrement, the count will be wrong

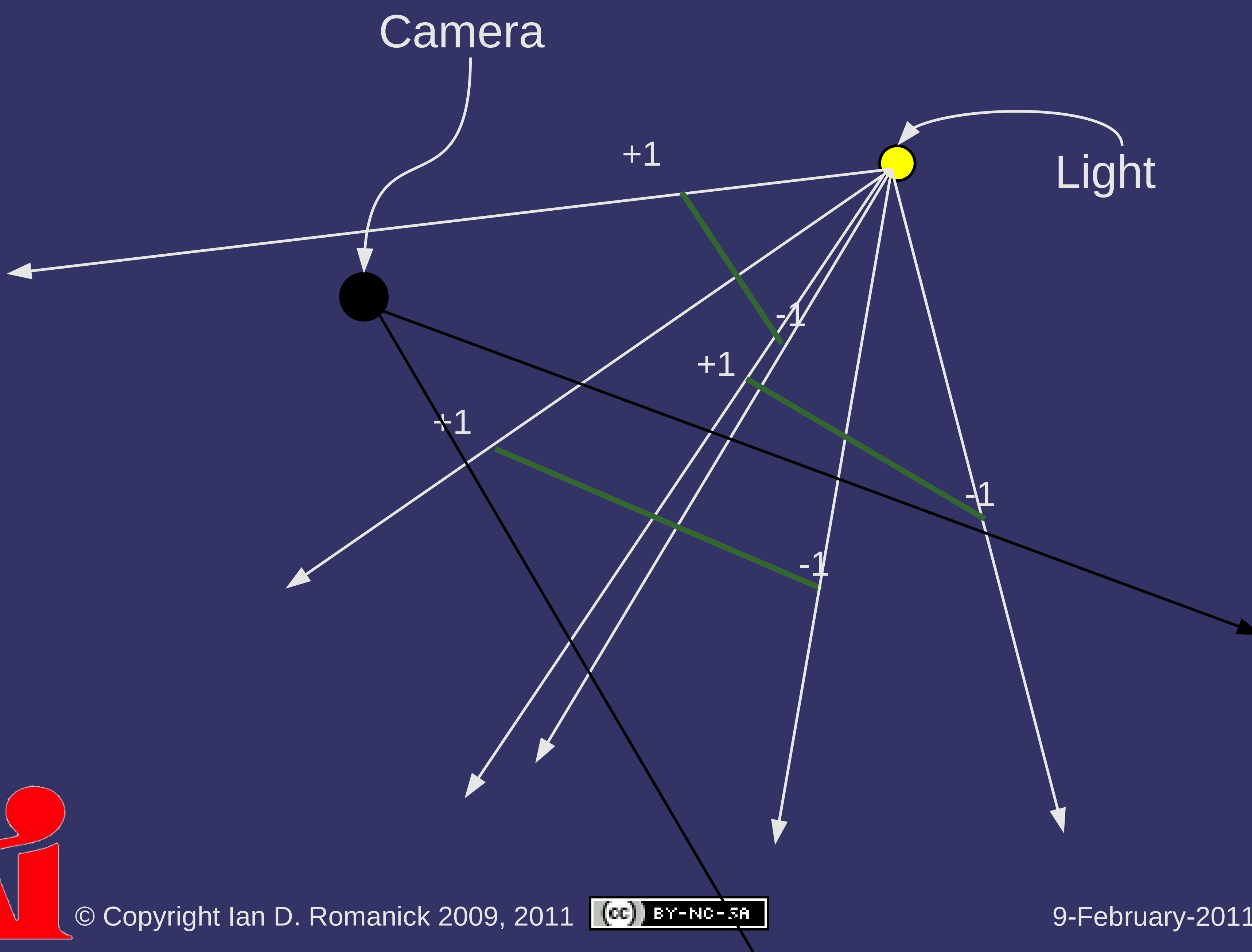
Shadow Volumes – Z-Pass



Shadow Volumes – Z-Pass

- Big problem with z-pass: What if the camera is *inside* a shadow volume?

Shadow Volumes – Z-Pass



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  - The count is too low!

Shadow Volumes – Z-Pass

- Big problem with z-pass: What if the camera is *inside* a shadow volume?
  - The count is too low!
- Possible solutions:
  - Clear stencil buffer to +1 for each volume the camera is inside
    - Expensive to compute
  - Add a "cap" at the near plane for each volume the camera is inside
    - Expensive to compute
  - Use z-fail

Shadow Volumes – Z-Fail

1. Disable depth and color writes
2. Configure stencil operation:
   - `GL_INCR_WRAP` on depth fail back-faces
   - `GL_DECR_WRAP` on depth fail front-faces
   - `GL_KEEP` for all other cases
3. Draw shadow volumes

- Method first *publicly* described by John Carmack while working on Doom 3
  - Often called *Camack's reverse*

Shadow Volumes – Z-Fail

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2. Configure stencil operation:
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   - GL_DECR_WRAP on depth fail front-faces
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3. Draw shadow volumes

Note that the depth test and the polygon facing are reversed compared to z-pass

Shadow Volumes – Z-Fail

- Big problems with z-fail:
  - Since more geometry fails the depth test than passes, this method can use orders of magnitude *more* fill rate
  - US Patent #6,384,822

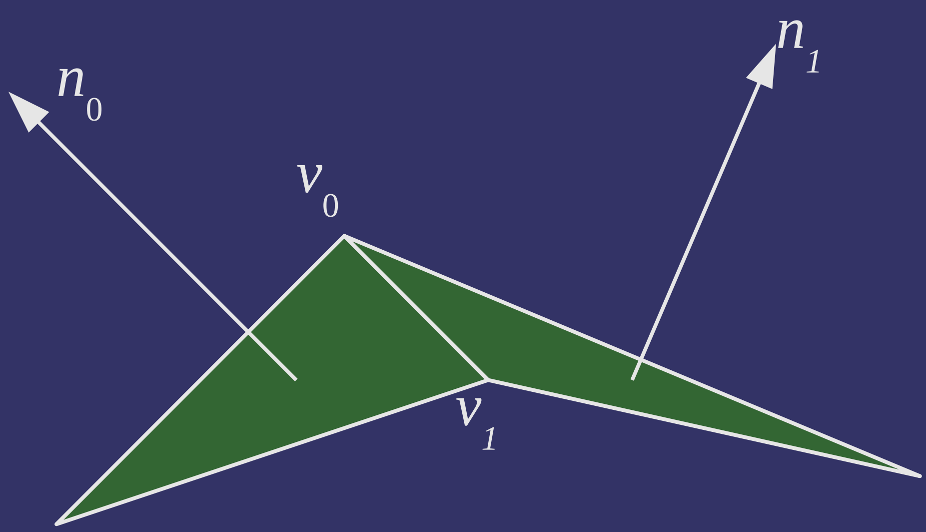
Shadow Volumes

- Shadow volume geometry is made of 3 types of polygons:
  - Front faces of the object (w.r.t. the light)
  - Quads from each silhouette edge (w.r.t. the light) projected to “infinity”
  - Back faces of the object (w.r.t. the light) projected to “infinity”

Shadow Volumes

- Front and back caps are trivial. What about the sides?
  - Add a degenerate quad at each edge of the model
  - Quad stores normals of one polygon with one vertex pair and normals of the other polygon with the other vertex pair
  - In vertex shader, test vertex normal against light. If normal points away from light, project to infinity
    - For silhouette edges one pair will be projected away and the other pair will not

Shadow Volumes



Vertex data for shadow volume quad:

v0	n0
v1	n0
v1	n1
v0	n1

Shadow Volumes

- Advantages?
  - Shadow volume geometry is independent of light position and object orientation
  - Very little work done on the CPU per-frame
  - Static shadow volume data does not need to be re-uploaded to GPU every frame
- Disadvantages?
  - For static lights and geometry a *lot* of redundant work is done every frame
  - True shadow volumes only exist on the GPU, so we can't determine whether the camera is inside a shadow volume

References

http://en.wikipedia.org/wiki/Shadow_volume

Shadow Volume Geometry

- Generating shadow volume geometry directly from raw vertex data is *hard*
  - Clearly some data structure is needed to make the work easier
- What features must this data structure have?

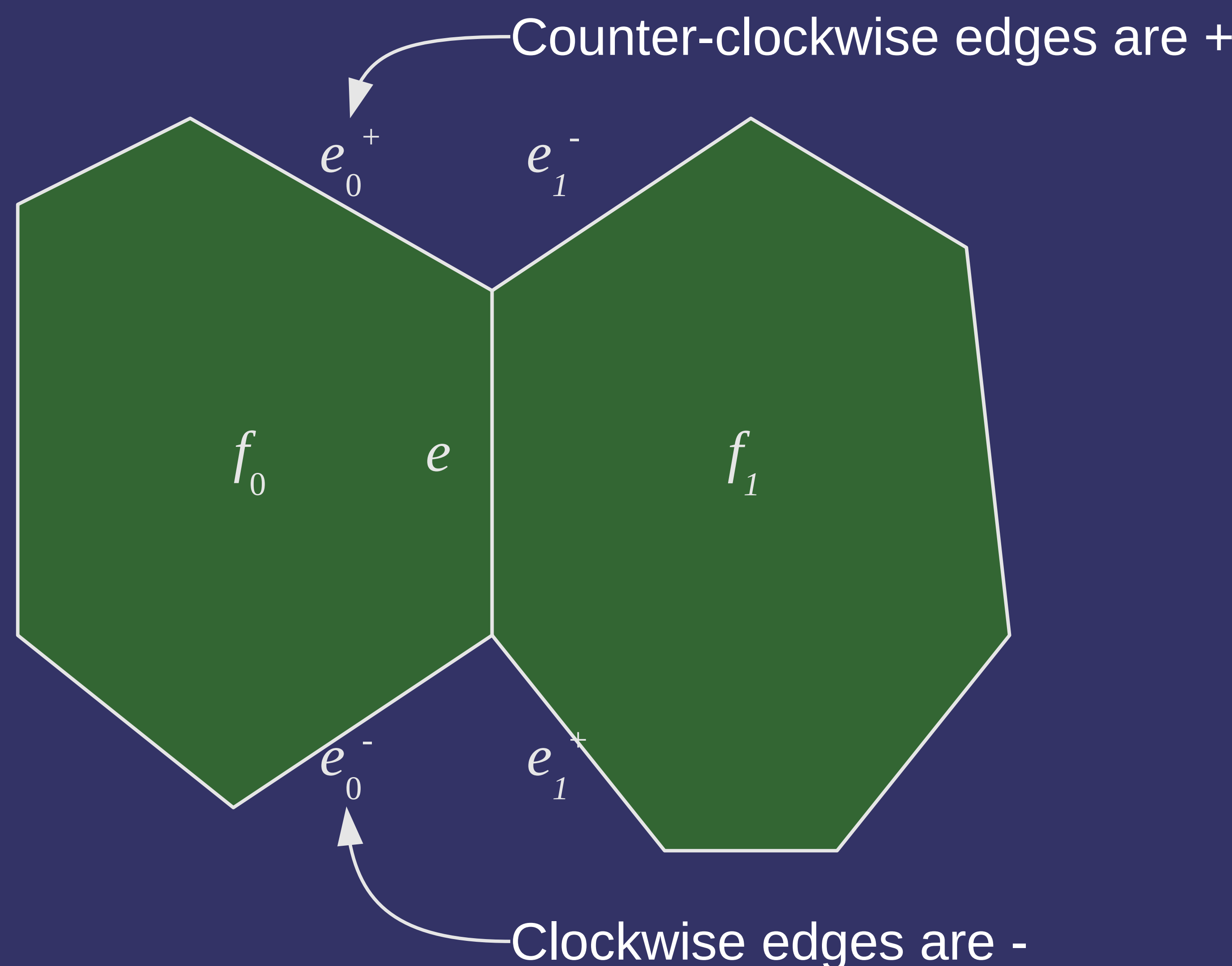
Shadow Volume Geometry

- Generating shadow volume geometry directly from raw vertex data is *hard*
  - Clearly some data structure is needed to make the work easier
- What features must this data structure have?
  - Iterate over each edge in the mesh *exactly once*
  - Access to each polygon sharing an edge
  - Access to neighboring edges in each polygon
    - This is so that normals can be calculated
- Does such a magical data structure exist?

Winged-Edge Mesh

- The *original* mesh structure to store connectivity information
- As the name implies, the focus is the *edge*
  - Each vertex stores a pointer to one of the edges "radiating" from it
  - Each polygon stores a pointer to one of its edges
  - Each edge has 8 pointers:
    - Pointers to each of its vertices (2)
    - Pointers to each of its polygons (2)
    - Pointers to each of its connecting edges (4)

Winged-Edge Mesh



Winged-Edge Mesh

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  - Ease of manipulation: adding and removing data should not be too expensive
  - Scalability: May want to trade data size for performance per the needs of the application

Winged-Edge Mesh

- Desirable mesh representation properties:
  - Ease of manipulation: adding and removing data should not be too expensive
  - Scalability: May want to trade data size for performance per the needs of the application

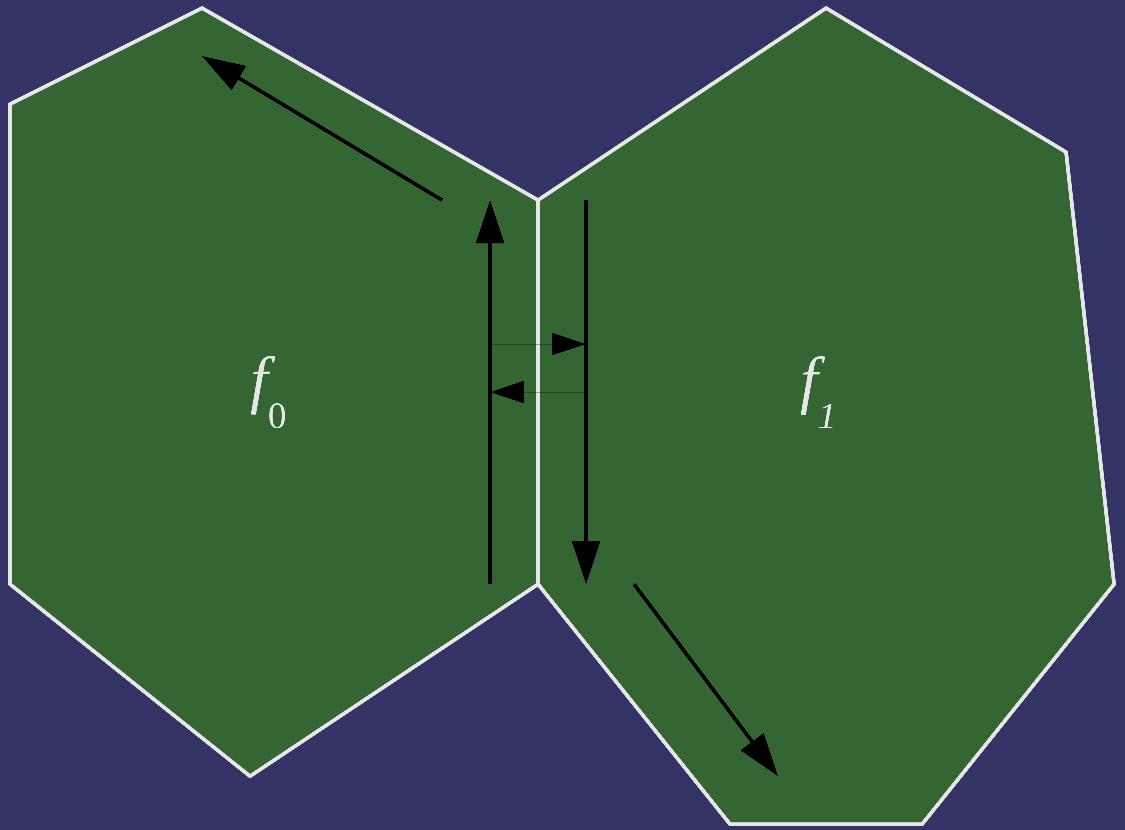
- Several common types of updates on WE meshes are *really* complicated to implement correctly

- Base winged-edge lacks the ability to iterate over the edges
- Base winged-edge has a *lot* of extra pointers that we will never use

Half-Edge Mesh

- Slight modification of winged-edge mesh:
  - Half-edge (HE) structures replace (full) edges
  - Each HE stores 4 pointers:
    - Pointer to starting vertex (1)
    - Pointer to polygon (1)
    - Pointer to counter-clockwise neighbor HE on the same polygon (1)
    - The “opposite” HE (1)
      - I call this the *sibling edge*
      - Other references call it *symmetric edge* or *pair edge*

Half-Edge Mesh



Half-Edge Mesh

```
struct half_edge {
    // Pointer to next counter-clockwise edge on same
    // polygon
    struct half_edge *next_ccw;

    // Pointer to matching edge on different polygon
    struct half_edge *sibling;

    // Pointer to the owning polygon
    struct polygon *p;

    // Pointer to next edge in global mesh edge list
    struct half_edge *next;

    // Pointer to starting vertex
    struct vertex *v;
};
```

Half-Edge Mesh

- If each HE only stores one vertex pointer, how do we get the other end?

Half-Edge Mesh

- If each HE only stores one vertex pointer, how do we get the other end?
  - The sibling edge stores a pointer to the other vertex
  - `e->v` and `e->sibling->v` make up the complete edge

Half-Edge Mesh

```
struct vertex {
    // Pointer an edge leaving this vertex
    struct half_edge *edge;

    // Pointer to position data for this vertex
    GLUvec4 *v;
};
```

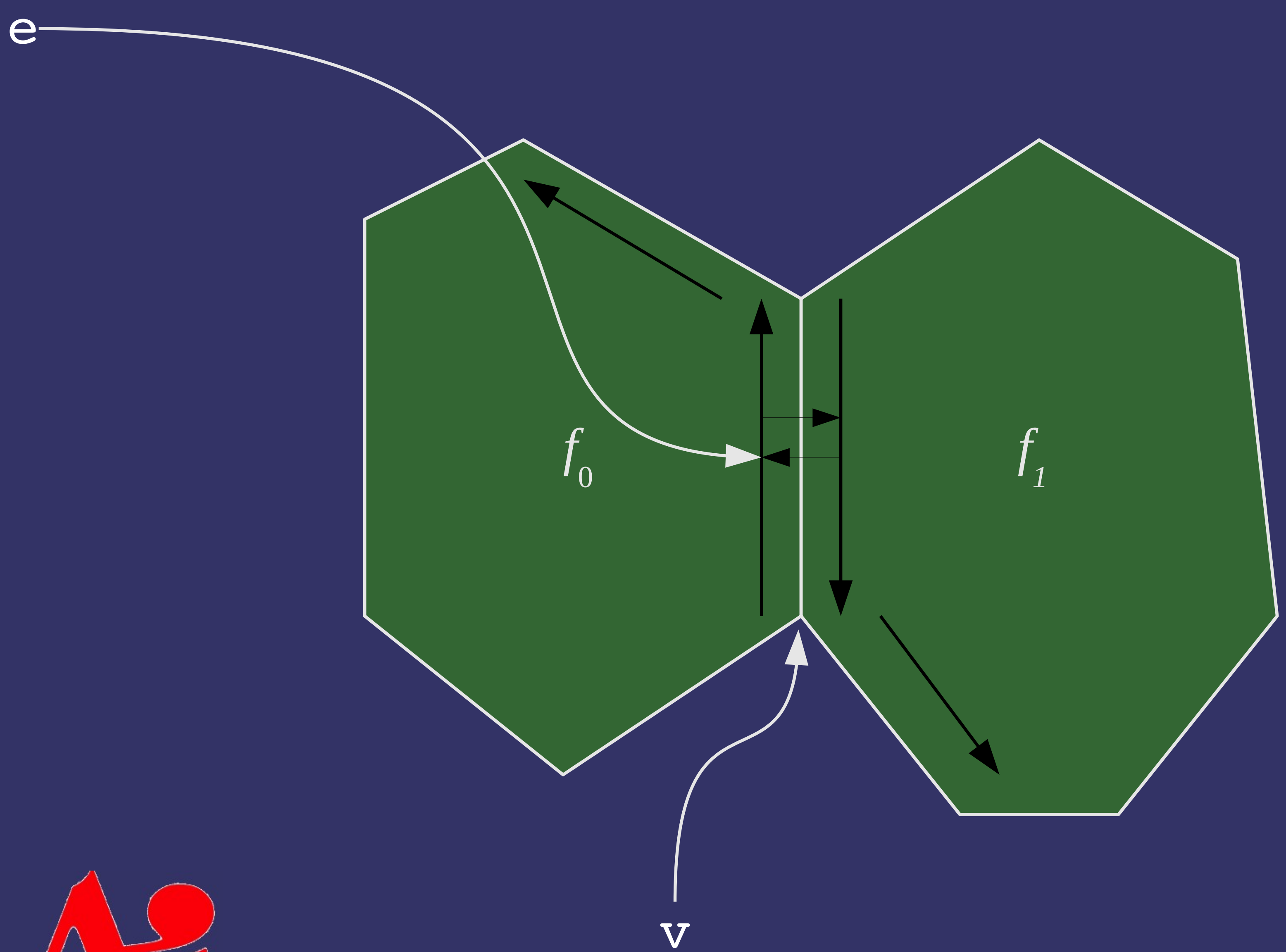
Half-Edge Mesh

- Given a vertex structure, how can we iterate all the edges that share that vertex?

```
half_edge *e = v->edge;
do {
    // Do real work here.

    // Iterate to next edge
    e = e->sibling->next_ccw;
} while (e != v->edge);
```

Half-Edge Mesh



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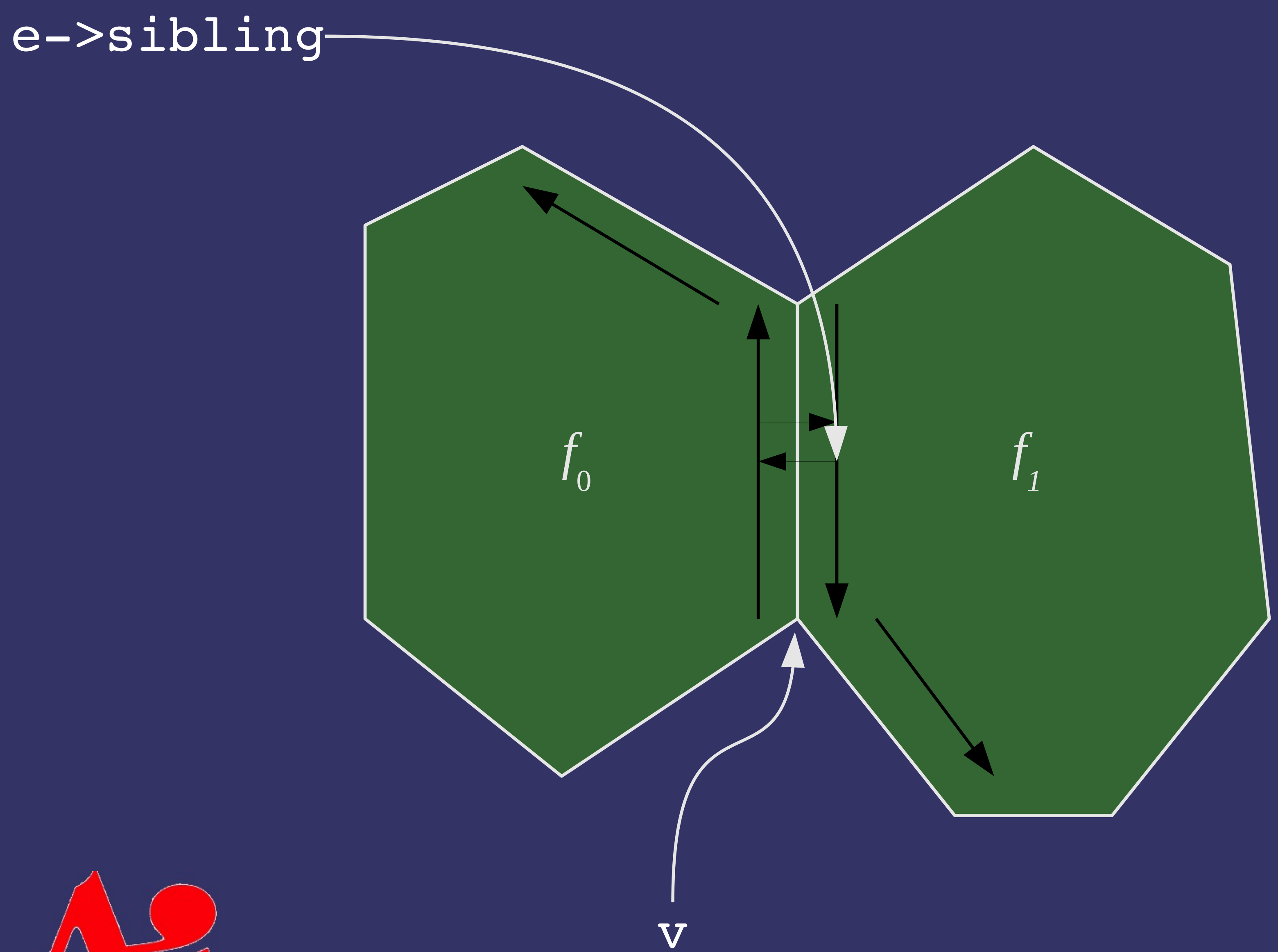

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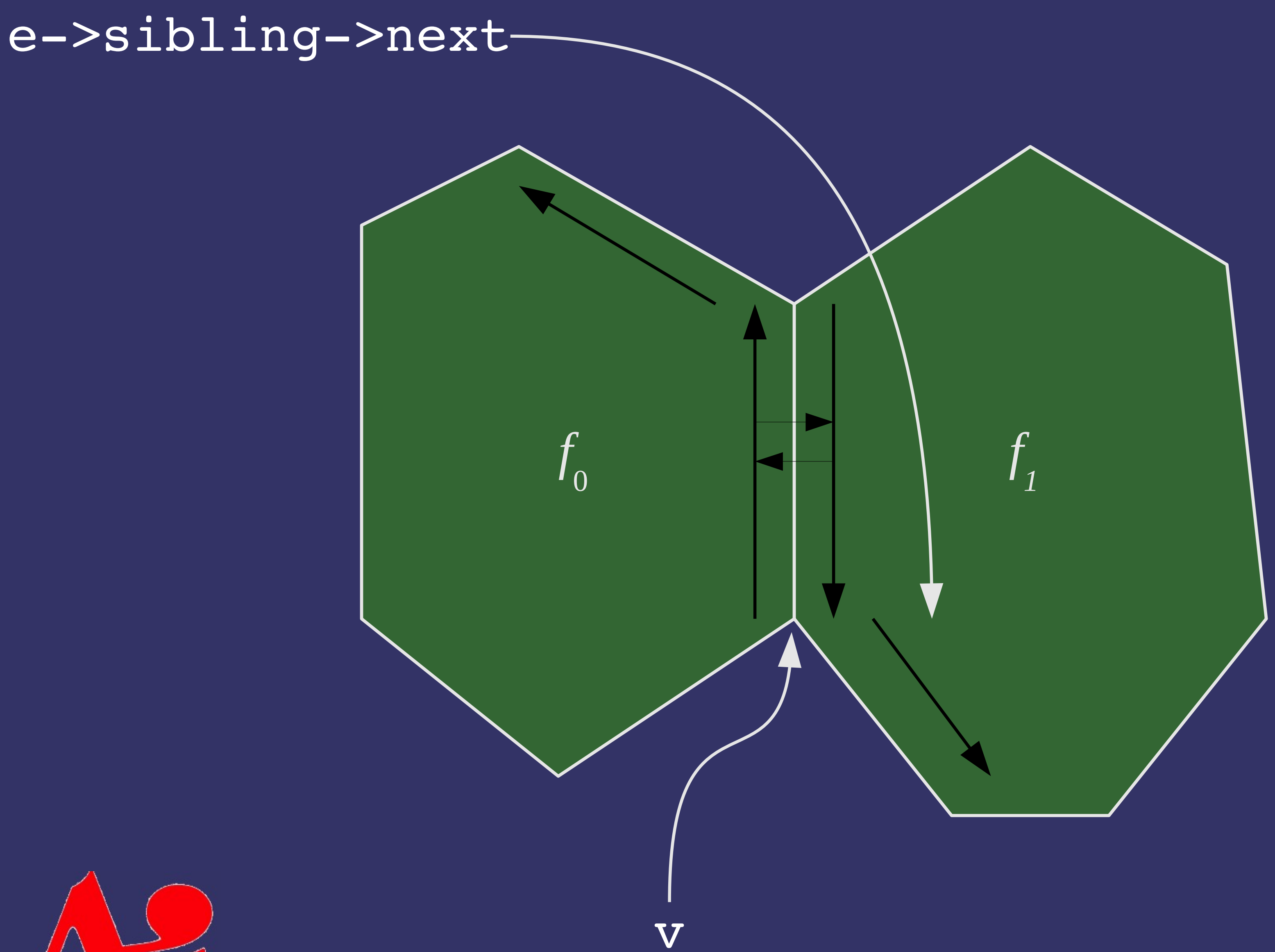
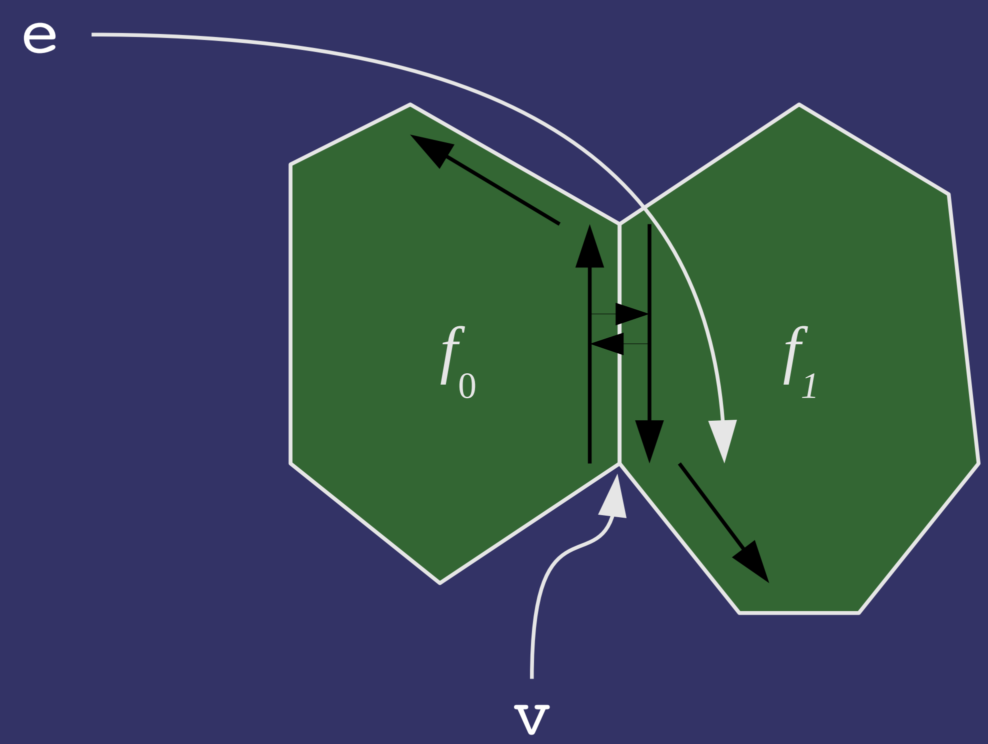


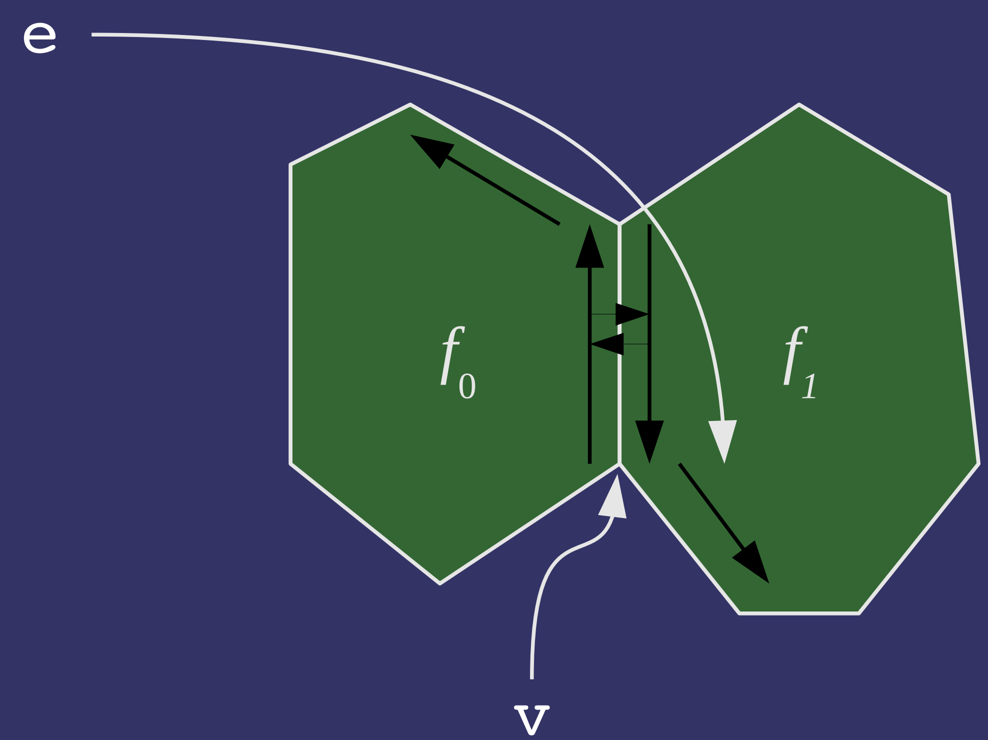
Half-Edge Mesh

- What's the problem?



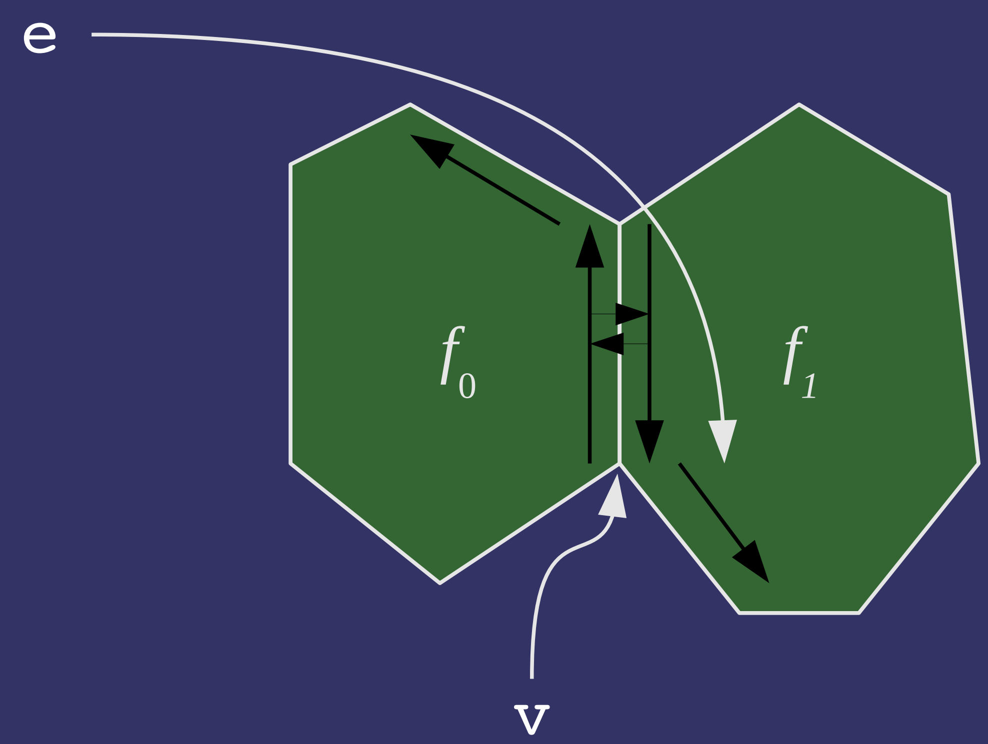
Half-Edge Mesh

- What's the problem?
  - The new e doesn't really have a sibling!
  - There are no pointers to follow to get the next edge



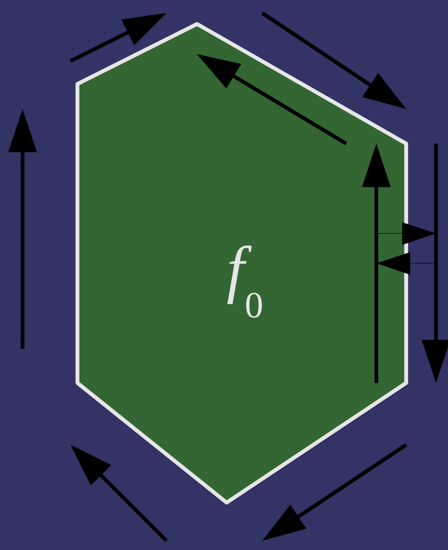
Half-Edge Mesh

- How can we add new edges to the mesh and prevent this problem?



Half-Edge Mesh

- How can we add new edges to the mesh and prevent this problem?
  - As new polygons are created, the sibling edges are linked in a “fake” CCW ring
    - The polygon pointers of these HEs is `NULL`
  - Adding *new* edges is a matter of updating all the linked lists



Half-Edge Mesh

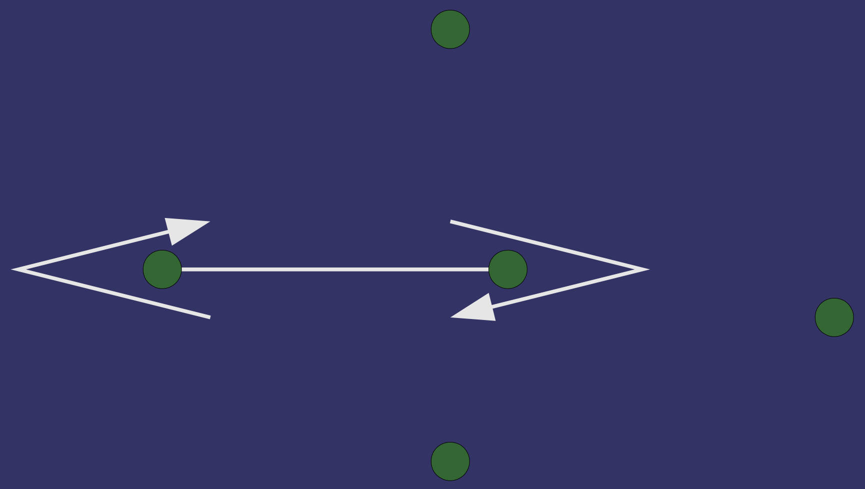
- To make the HE work, there are a few more primitives required
  - `create_edge(v0, v1)`: Create a new pair of HEs between `v0` and `v1`
  - `make_adjacent(a, b)`: Link `a` and `b` so that `a->next = b`
  - `add_polygon(edges, n)`: Create a new polygon from a list of existing edges

Half-Edge Mesh

- To create a *new* edge:
  - Allocate two HEs, link one to `v0` and the other to `v1`
  - Set both polygon pointers to `NULL`
  - Link both HEs as siblings
  - Link both HEs as each others `next_ccw`
    - Tricky! This makes the bootstrap case work and fixes other issues in `make_adjacent`
  - Insert each edge in the “gap” in the vertex's edge list
    - Some HE where:
      - `e->sibling->v == v`
      - `e->p == NULL`
      - `e->next_ccw->v == v`

Half-Edge Mesh

- Edges can be added in arbitrary order...



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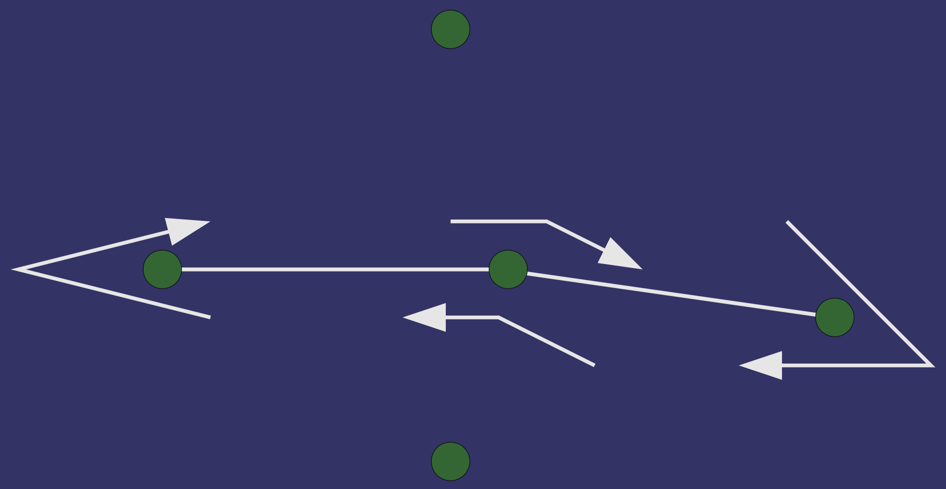

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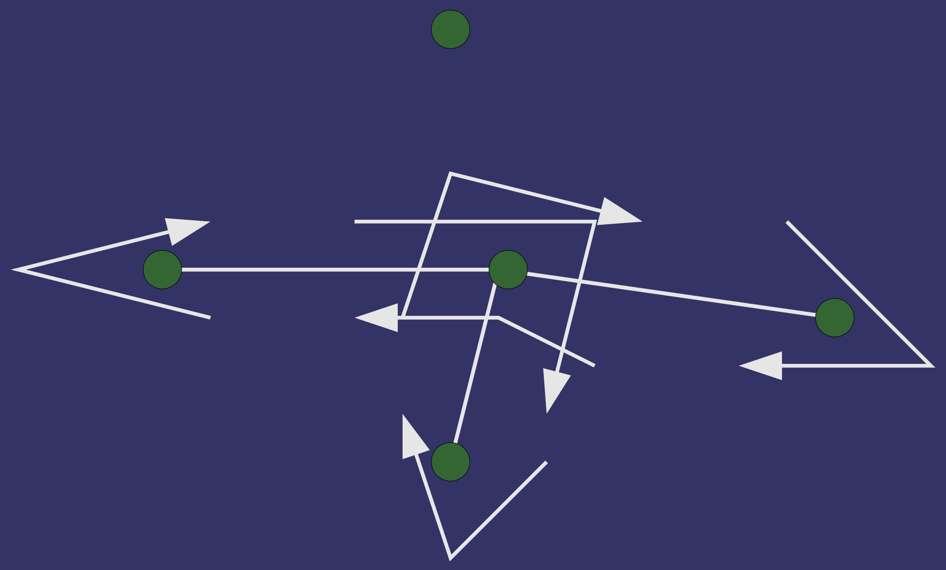

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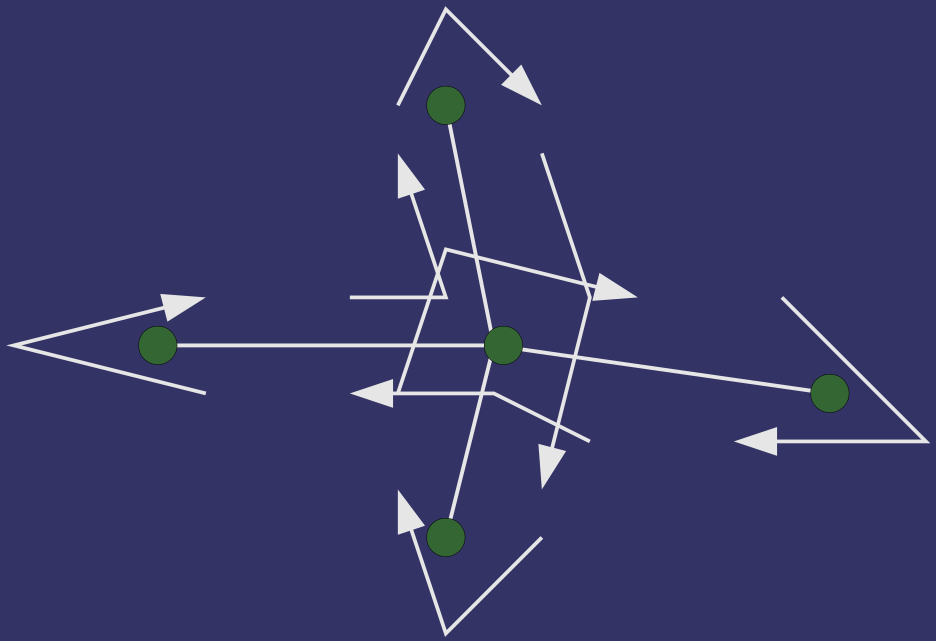

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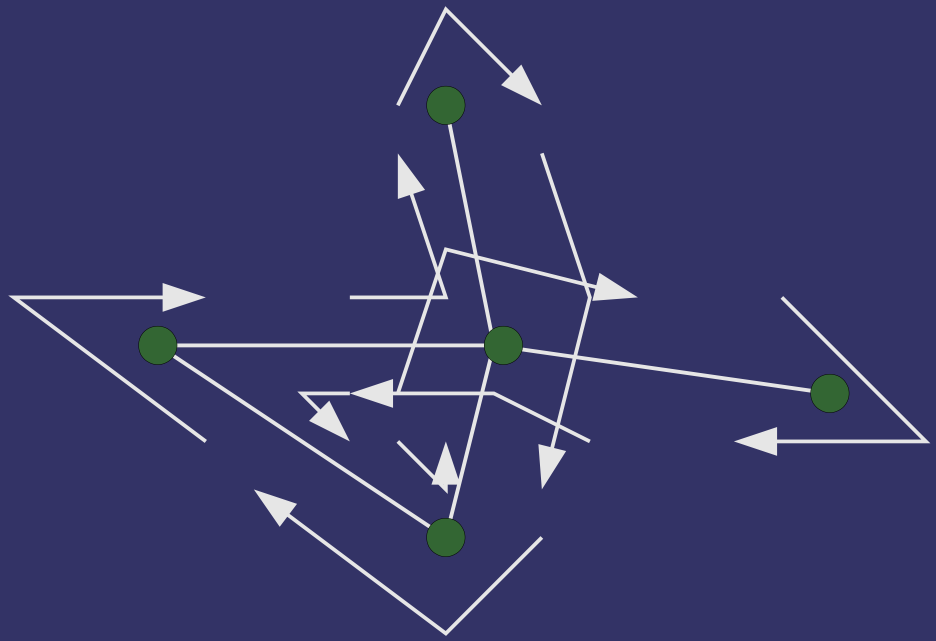
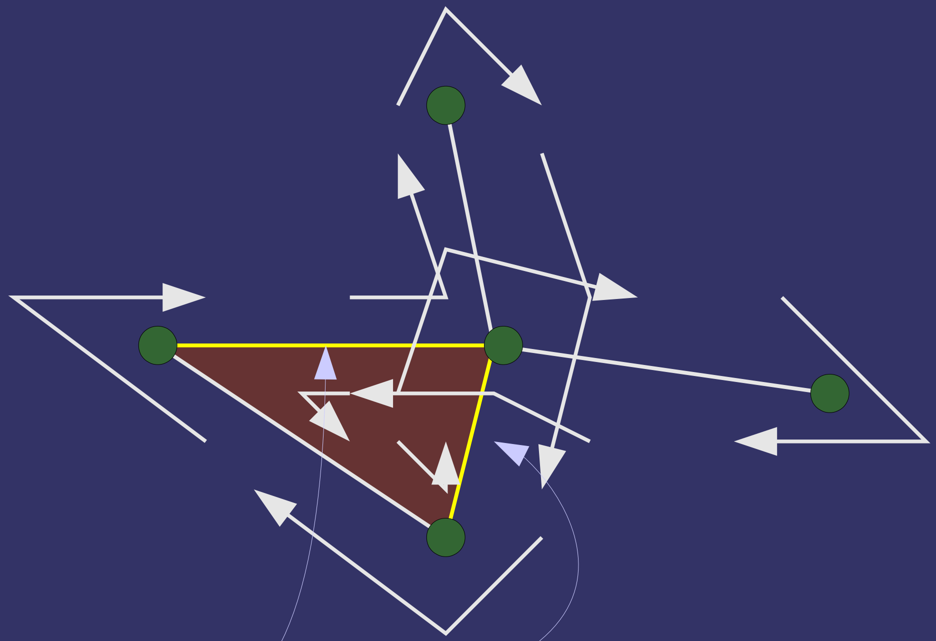


Half-Edge Mesh

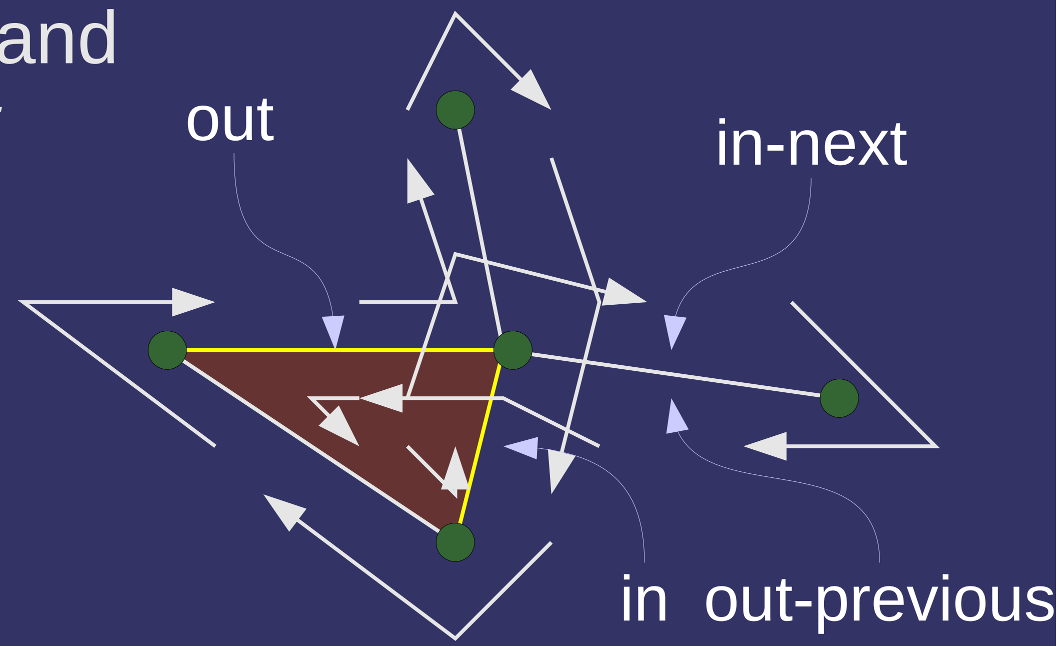
- Edges can be added in arbitrary order...
  - This causes problems when edges are formed into a polygon



These edges should be linked

Half-Edge Mesh

- Relink the edges to create the correct relationships
  - Cut the links between *in* and *in-next*, and between *out* and *out-previous*



Half-Edge Mesh

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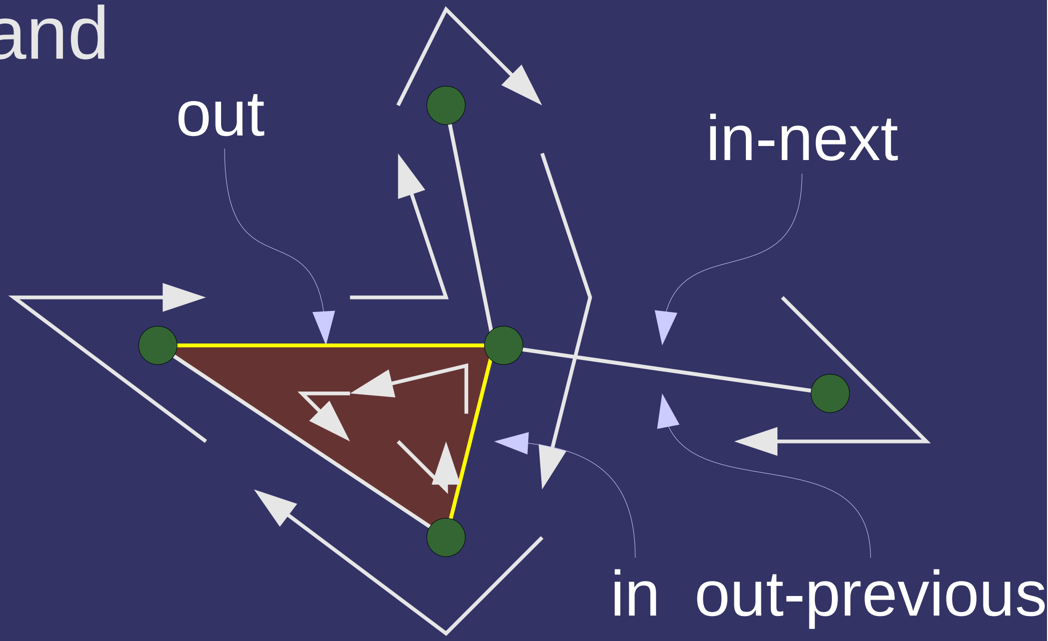

Half-Edge Mesh

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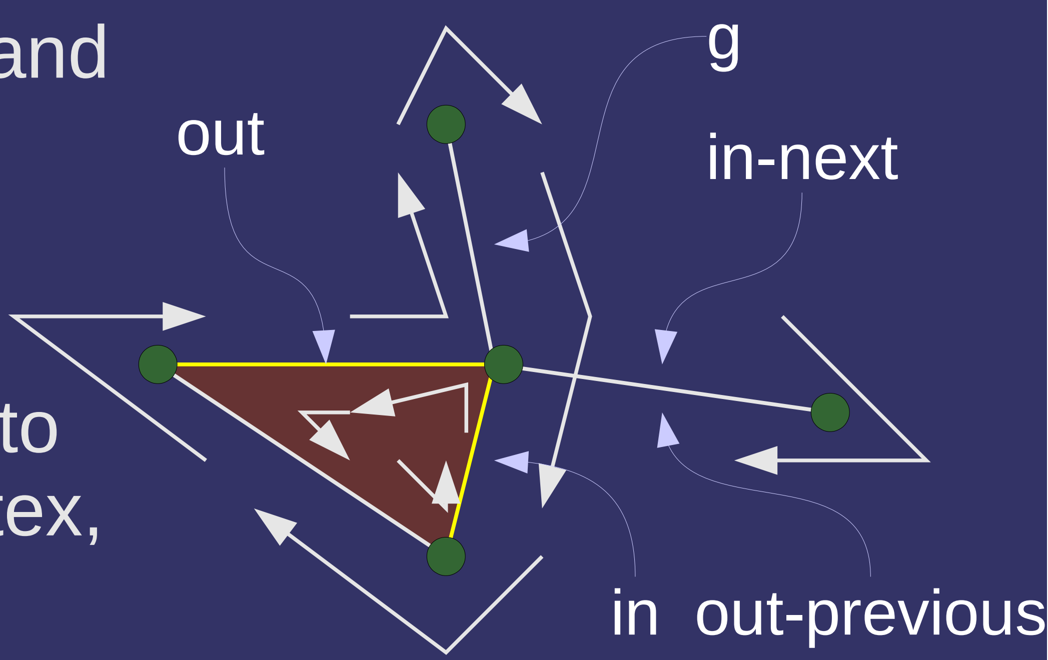
  - Cut the links between *in* and *in-next*, and between *out* and *out-previous*
  - Link *in* and *out*
  - Find a free edge going into *in* and *out's* common vertex, call it *g*
    - This edge must be between *out-sibling* and *in*



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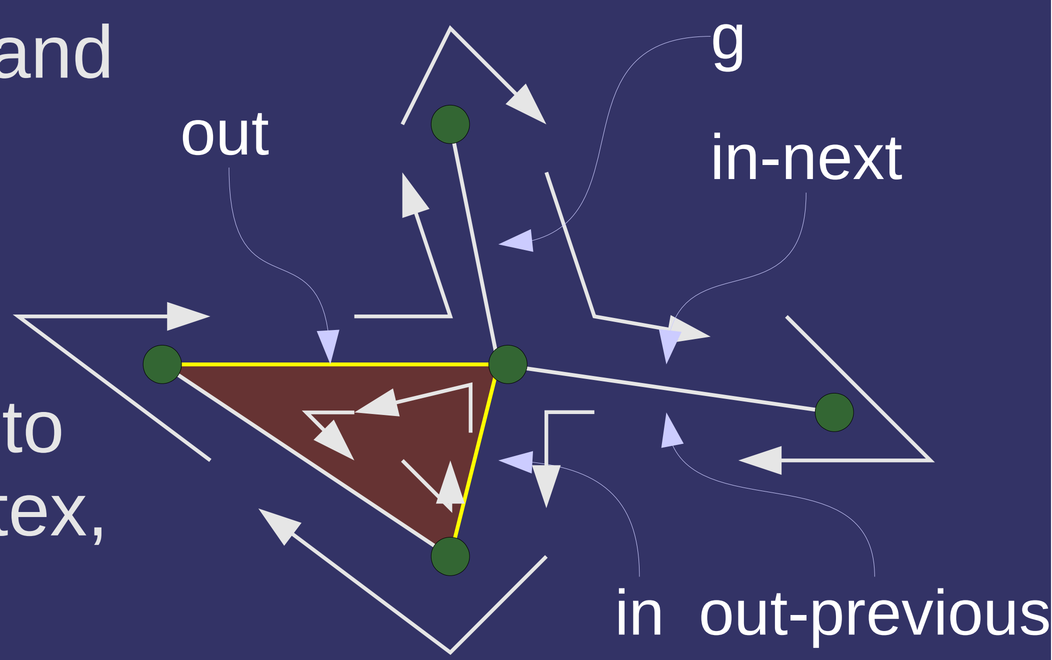

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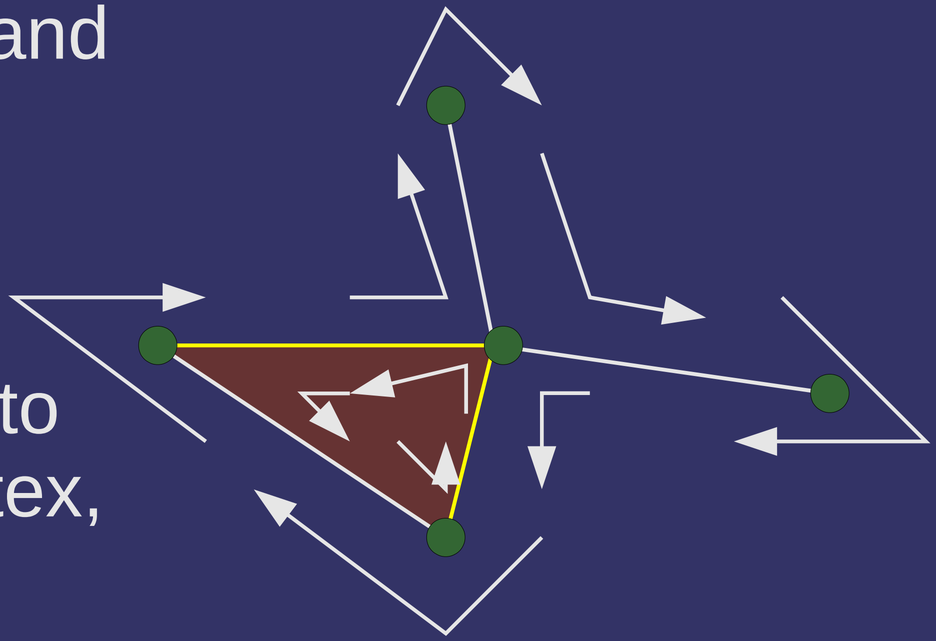

Half-Edge Mesh

- With these primitives, adding a new polygon is easy
  - For all edges, verify that the end point of one edge and the start point of the next edge is the same
  - For all edges, verify that the edge is not already associated with a polygon
  - For all edges, connect the edge to the next edge in the list
  - Allocate a new polygon object and connect all of the edges to it

References

Matt Pharr and Ken Schoemake, ed. *comp.graphics.algorithims FAQ.* Accessed 13 May 2008; available from http://cgafaq.info/wiki/Geometric_data_structures; Internet.

Shadow Volume Geometry

- Once we have a model stored half-edge or winged-edge data structure, how do we generate the shadow volume geometry?

Shadow Volume Geometry

- Once we have a model stored half-edge or winged-edge data structure, how do we generate the shadow volume geometry?
  - For each edge in the mesh:
    - If the either of the edge's polygon pointers is `NULL`, skip the edge
    - Calculate the normal of each polygon sharing the edge, call these n_0 and n_1
    - If n_0 and n_1 are equal, skip the edge
      - This happens if the surfaces are co-planar, and can *never* be on the silhouette
    - Emit a quad of (v_0, n_0), (v_1, n_0), (v_1, n_1), (v_0, n_1)

Fixing Object Geometry

- What about edges with `NULL` polygon pointers?

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  - These represent *holes* in the model
    - The Stanford bunny model has several holes in the bottom
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- What about edges with `NULL` polygon pointers?
  - These represent *holes* in the model
    - The Stanford bunny model has several holes in the bottom
  - For each hole, the hole-edges form a ring
- What can we do with this?
  - Walk the hole-edge ring and insert *new* edges between each pair of hole-edges
  - Each new edge will form a triangle that fills part of the hole
  - Do this step *before* generating shadow volume geometry

Next week...

- Advanced shadow volume techniques:
  - Fixing z-pass and z-fail with ZP+
  - Soft shadows using shadow volumes
  - Hardware based optimizations:
    - Depth clamping
    - Depth bounds testing

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