Building 3D Models Using Plastic Construction Bricks

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Outline

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- Motivation
- Representing 3D Models As Voxels
- Representing 2D Images As Voxels
- Converting Voxels To Plastic Construction Bricks
- Results

Motivation

Problem Definition

Problem: Given a three-dimensional model how can we build that model using plastic construction bricks?

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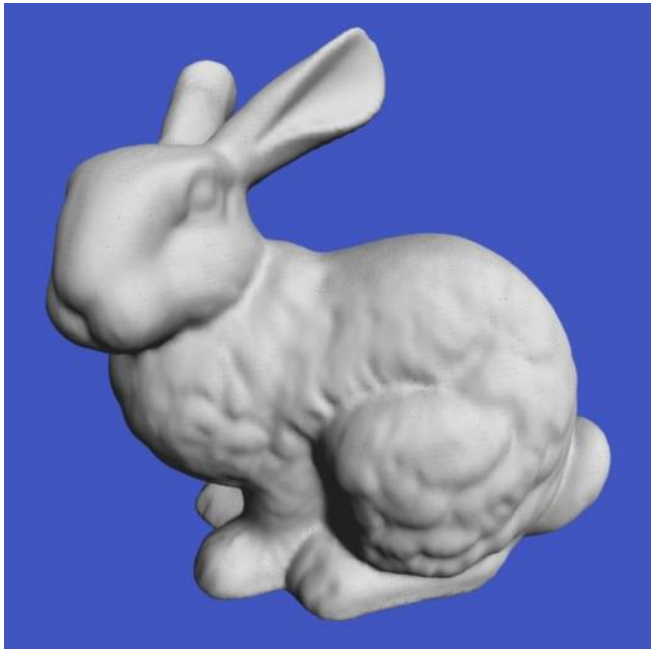
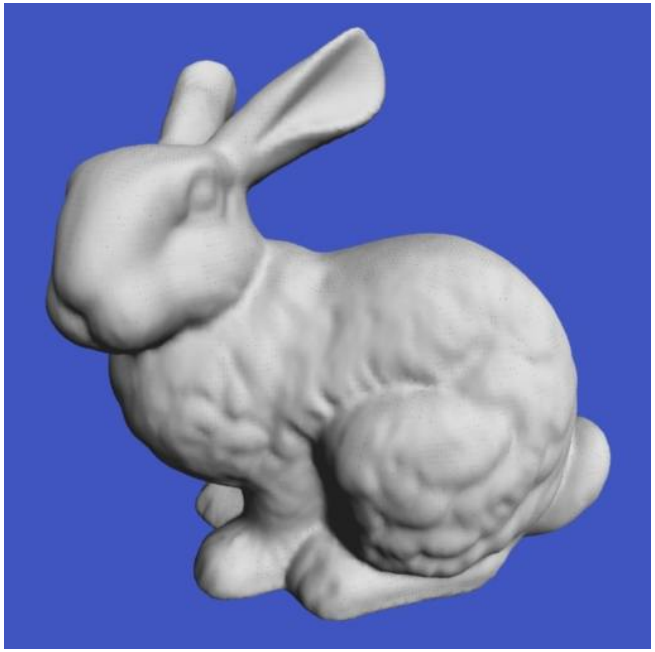
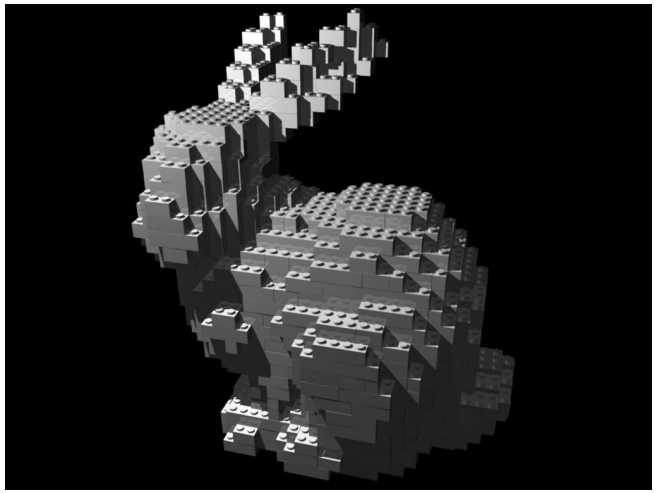
Our answer: Create a voxelization of the model, then represent that voxelization as a set of LDraw parts which have been carefully selected to produce a buildable version of the model.

Problem In Pictures



Problem In Pictures





Motivation

- Artistic expression
  - Mosaics
  - Sculptures
  - Music videos
  - Animations

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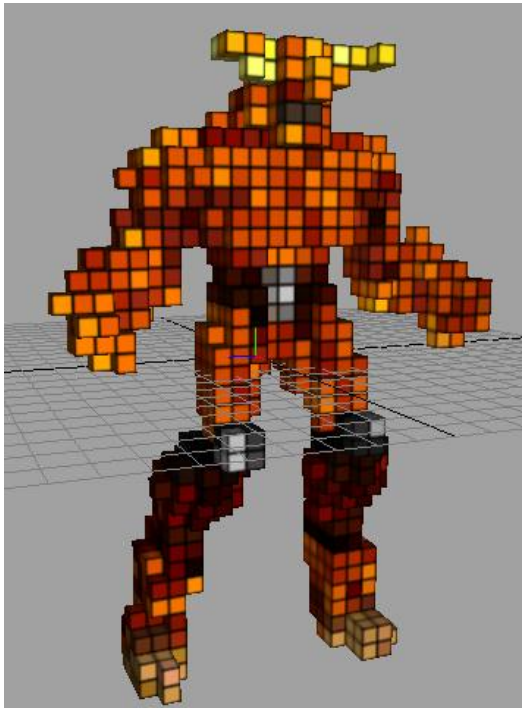
  - Animations
- Technical idea + creativity ⇒ publication
- Block construction turns out to be an interesting problem

Representing 3D Models As Voxels

Voxelization

- Given a polygonal model, generate a set of voxels



What is a voxel?

- A small 3D box with some properties (density, color, etc)
- Short for volume element
- 3D counterpart of a 2D pixel

Voxelization

- Process of converting a geometric representation of a synthetic model into a set of voxels
- Some processes are easier to use when operating on voxel data
  - Computing Volume
  - CSG (Intersection, Union, etc)
  - Collision Detection
- The reverse is also true; Voxels are not optimal for everything

Voxelization

- Several methods for generating a voxelization exist
  - Casting Rays
  - Scan Converting
- Most are not pretty to code
- Can be slow
- Can we speed it up? Yes, use the GPU

See http://www.cs.sunysb.edu/ vislab/projects/volume/Papers/Voxel/

Hardware Accelerated Voxelization

- Modern graphics hardware is fast (exceeding Moore's Law)
- Modern graphics hardware is programmable
- Computationally expensive algorithms are being offloaded to the GPU
  - Fast Fourier Transform
  - Global Illumination Computations
  - Path Finding (AI)
  - Collision Detection

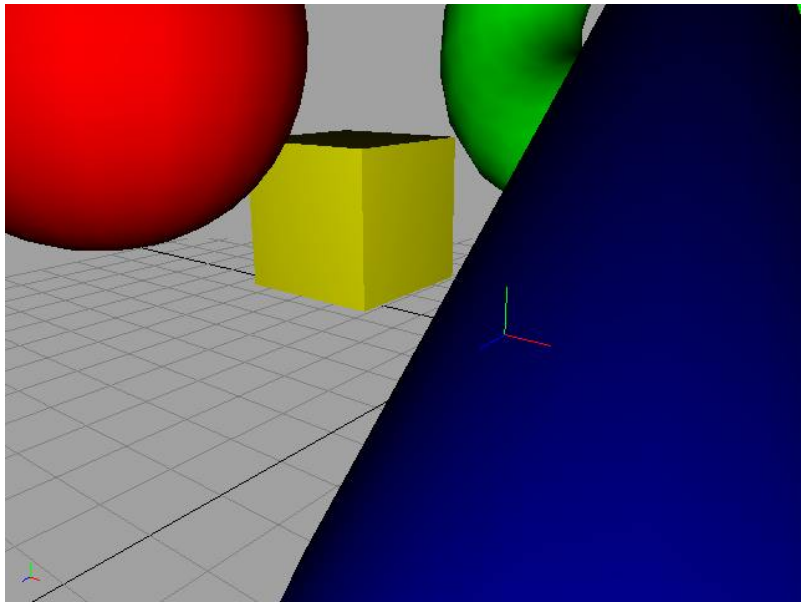
Hardware Accelerated Voxelization

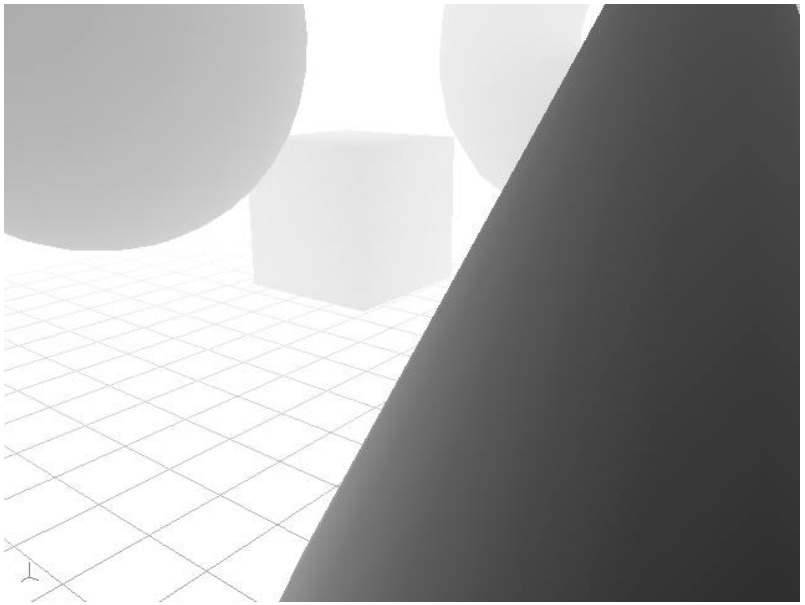
- Turns out we don’t need to use the programmable GPU
- Standard fixed function color and depth buffers will suffice
- Color buffer stores the color of each pixel in the rendered scene
- But what is the depth buffer?

Depth Buffer

- Also known as the Z-buffer
- Stores the depth of each pixel in the scene
- Values range from [0,1]
- Usually initialized to 1
- Smaller values are closer to the near clip plane (camera)
- Traditionally used for hidden surface removal

Depth Buffer Example



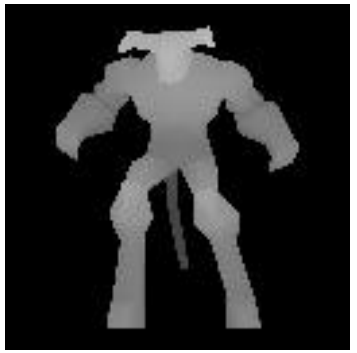


HW Voxelization Algorithm

- Center mesh around world origin
- Set viewport to N×N, where N is the size of a dimension in the N×N×N voxel lattice
- Render scene through a tightly fitted orthographic (parallel) projection from each side of the model's bounding box
- Record depth and color buffers from each render
- Produces six set of images (6 color buffer images, 6 depth buffer images)

Depth/Color Buffer Visualization

- Front/Back

Depth/Color Buffer Visualization

- Left/Right

Depth/Color Buffer Visualization

- Top/Bottom




Determing if a Voxel is "On"

- For each voxel in the lattice, compute the distance to each side of the cube
- Test if this distance is bounded by the depth buffers in each axis
- If so, voxel is inside, otherwise, its outside
- Holes not visable from outside the object will be filled

Determining a Voxel's Color

- Find the depth map which is closest to the voxel
- Look up the voxel's color in the depth map's correspoding color map
- Interior voxels share the same color as closest surface voxel

Voxelization Algorithm Notes

- Works for polygonal and analytical models
- Efficiency is independent of model complexity
- Voxelizes data in $O(n)$
- Does not handle concave models

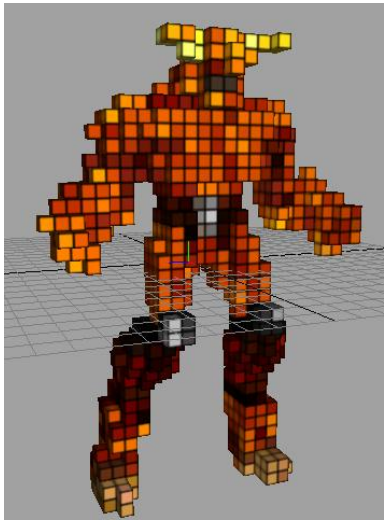
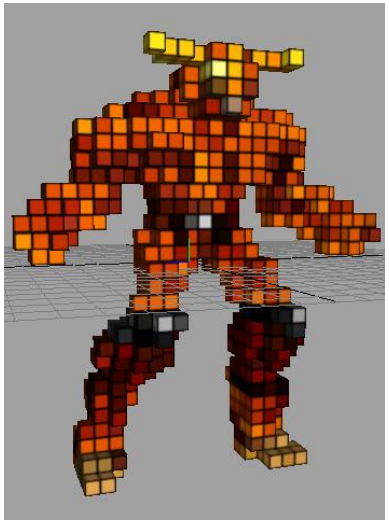
Voxel Visualization

- Can view voxel data as slices
- Viewing voxel data is useful for many application, specifically in medicine

See http://www.nlm.nih.gov/research/visible/visible_human.html

Plastic Construction Brick Specifics

- Plastic Construction Bricks are not cubes
- A 1×1 brick has a $\frac{5}{6}$ aspect ratio
- Model must be squashed during voxelization to perserve aspect ratio

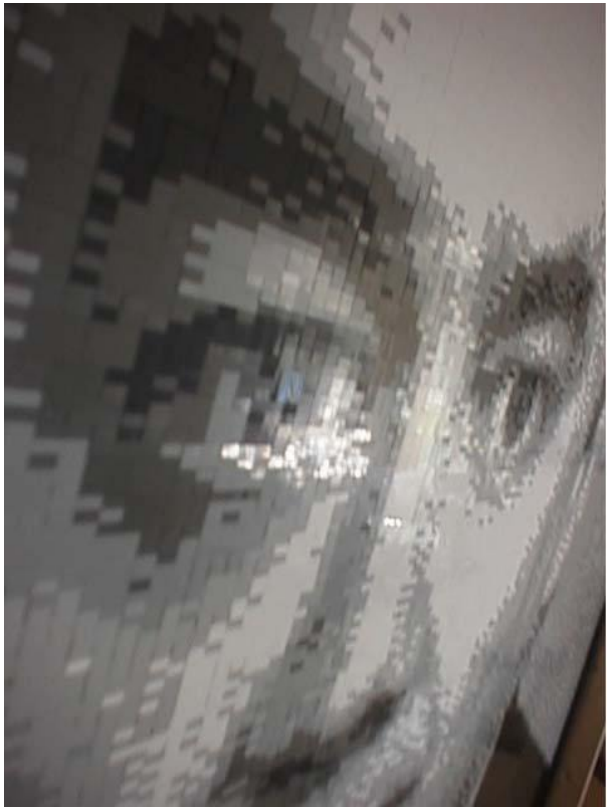
Demo

Representing 2D Images As Voxels

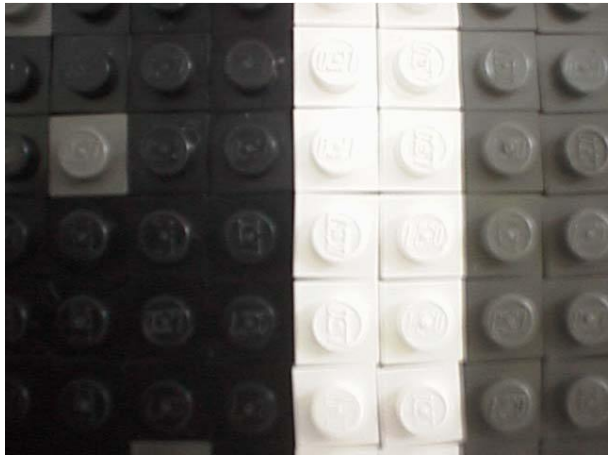
Voxelization of Images

- Goal: Given any 2D image, output a voxelization
- Pixels directly correspond to a voxel slice
- Perform image scaling to reduce/enlarge to desired number of voxels

Brick Mosaics

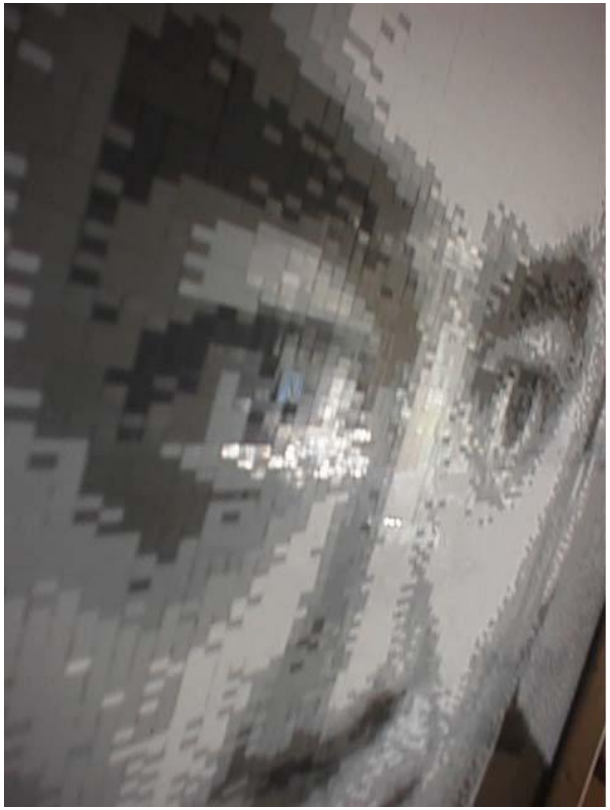


Studs-up

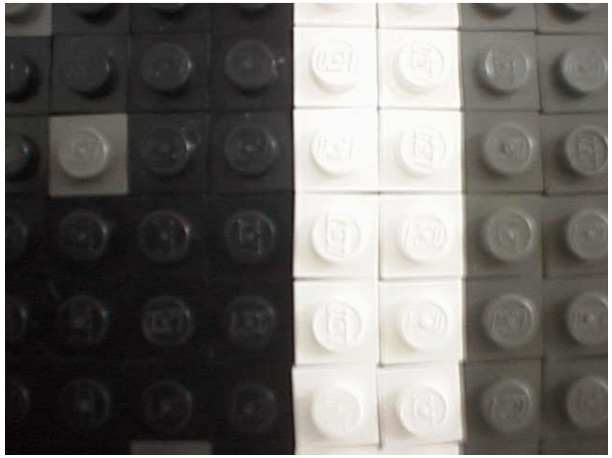


Studs-out

Brick Mosaics



Studs-up
X-Y plane



Studs-out
X-Z plane

Giving Voxels Color

- Platic Construction Bricks have a limited number of colors
- Convert image to brick palette
- Problem: Limited number of colors in brick palette causes banding

Converting to Brick Palette

- Solution: Dither the image
- Dithering is the addition of a sub-quantum signal (often high frequency noise) to a signal of interest that is being quantized
- Many dithering algorithms exist

Dithering

- We use Floyd-Steinberg dithering
- Spreads error in quantization over neighboring pixels



Generating a Construction Plan

- We use a simple greedy algorithm that processes 1 brick row at a time

Converting Voxels To Plastic Construction Bricks

What Is LDraw?

- Originally, DOS programs `LDraw` and `LEdit` with a file format representing several different plastic construction brick shapes
- Many editors have been developed using the LDraw parts file format
- Programs exist to convert to a variety of 3D applications
- Maintained by a standards committee now

LDraw File Format

- ASCII text
- First value is an integer indicating line type

#	**Line Type**
0	comment or meta-command
1	reference to another LDraw file
2	line between two points
3	triangle
4	quadrilateral
5	conditional line between two points

LDraw File Format (cont.)

- Reference line type is as follows:

  `1 <color> <transformation matrix> <file name>`

- Line between two points is as follows:

  `2 <color> <point1> <point2>`

- Triangle line type is as follows:

  `3 <color> <point1> <point2> <point3>`

- Quadrilateral line type is as follows:

  `4 <color> <point1> <point2> <point3> <point4>`

LDraw Conventions

Brick Sizes - given using a Width×Length×Height notation

Part Numbers - each different brick is given a unique part number; attempts to match those used by the LEGO™ Corporation

Colors - based on those used by the LEGO™ Corporation; each is assigned a unique integer

The Simple Answer

Replace each voxel with a 1x1 brick of the appropriate color. Interior voxels can be assigned any color desired.

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Replace each voxel with a 1x1 brick of the appropriate color. Interior voxels can be assigned any color desired.

Problem: This solution does not create a buildable version of the model.

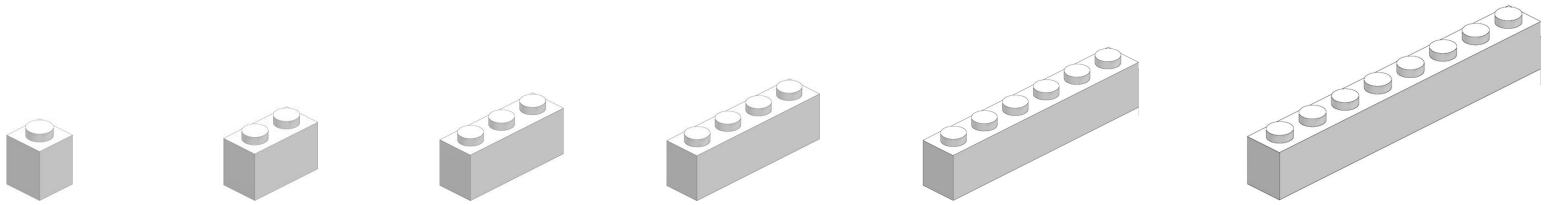
Algorithm Goals

- Replace neighboring voxels of the same color with an appropriate brick
- Check for support for a brick in the layer above or below
- Use $2 \times n$ bricks whenever possible
- Avoid 1×1 bricks whenever possible
- Fix building impossibilities

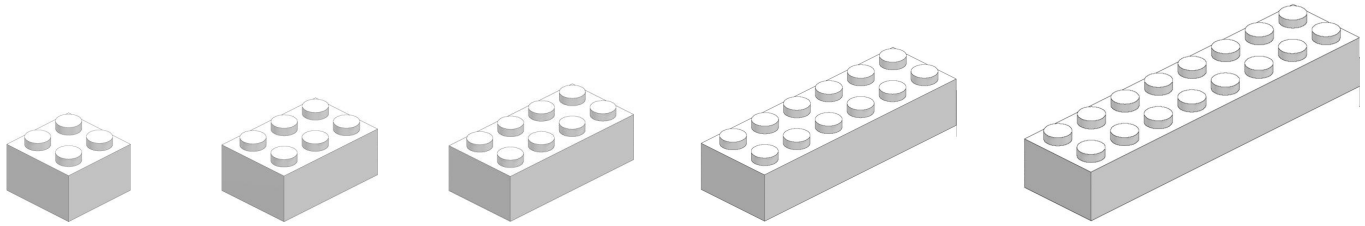
A Greedy Algorithm

- Voxelization is of size $x_{size} \times y_{size} \times z_{size}$
- Consider only an X-Z slice of the voxelization
- Search for adjacent voxels in the X direction first
- Search for adjacent voxels in the Z direction second
- Replace neighboring voxels with the largest brick possible

A Greedy Algorithm's Bricks



1×1 1×2 1×3 1×4 1×6 1×8



2×2 2×3 2×4 2×6 2×8

A Greedy Algorithm (cont.)

```
for (i=y_size − 1; i≥0; i--){
  for (k=0; k< z_size ; k++){
    j=0;
    while (j< x_size){
      start_x = FindFirstVoxelX();
      end_x = FindLastVoxelX();
      while(start_x ≤ end_x){
        length_x = end_x - start_x + 1;
        if (length_x == 1){
          start_z = k;
          end_z = FindLastVoxelZ();
          length_z = end_z - start_z + 1;
```

A Greedy Algorithm (cont.)

```
    if (length_z == 1)
      AddBrickZ(1×1);
    else if (length_z == 2)
      AddBrickZ(1×2);
    else if (length_z == 4)
      AddBrickZ(1×4);
    else
      AddBrickZ(1×3);
    start_x += 1;
  }
  else if (length_x%2 != 0){
    AddBrickX(1×3);
    start_x += 3;
  }
```

A Greedy Algorithm (cont.)

```
else if (length_x ≤ 8){
  AddBrickX(1×length_x);
  start_x += length_x;
}
else if (length_x == 10){
  AddBrickX(1×6);
  start_x += 6;
  AddBrickX(1×4);
  start_x += 4;
}
```

A Greedy Algorithm (cont.)

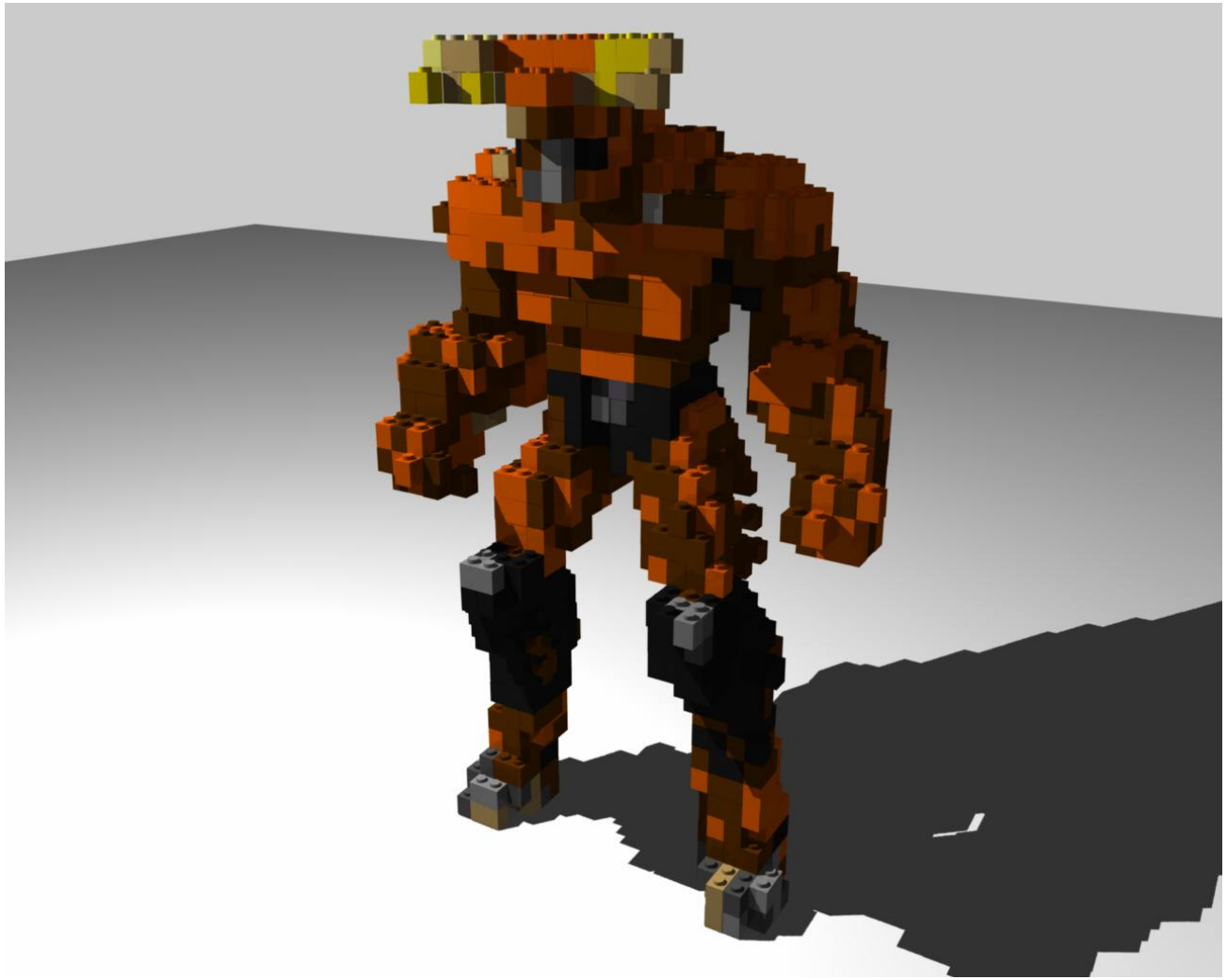
```
            else if (length_x == 12){
              AddBrickX(1×6);
              start_x += 6;
              AddBrickX(1×6);
              start_x += 6;
            }
            else{
              AddBrickX(1×8);
              start_x += 8;
            }
          }
          j = end_x + 1;
        }
      }
    }
```

Improvements

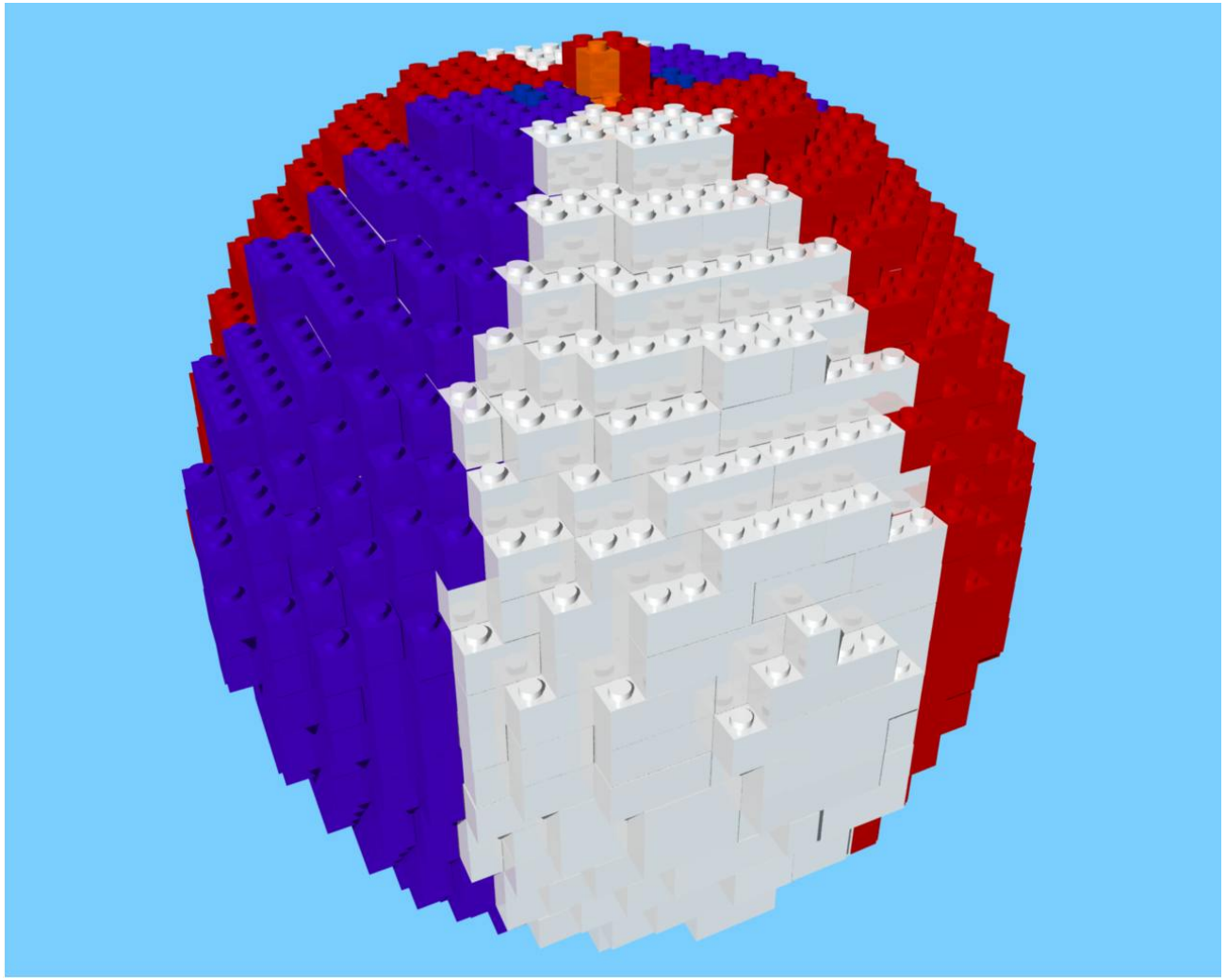
- Alternate primary greedy direction between X and Z
- Use L-shaped corner pieces
- Connect “floating” pieces
- Use bricks taller than 1
- Push smaller bricks to the center

Results

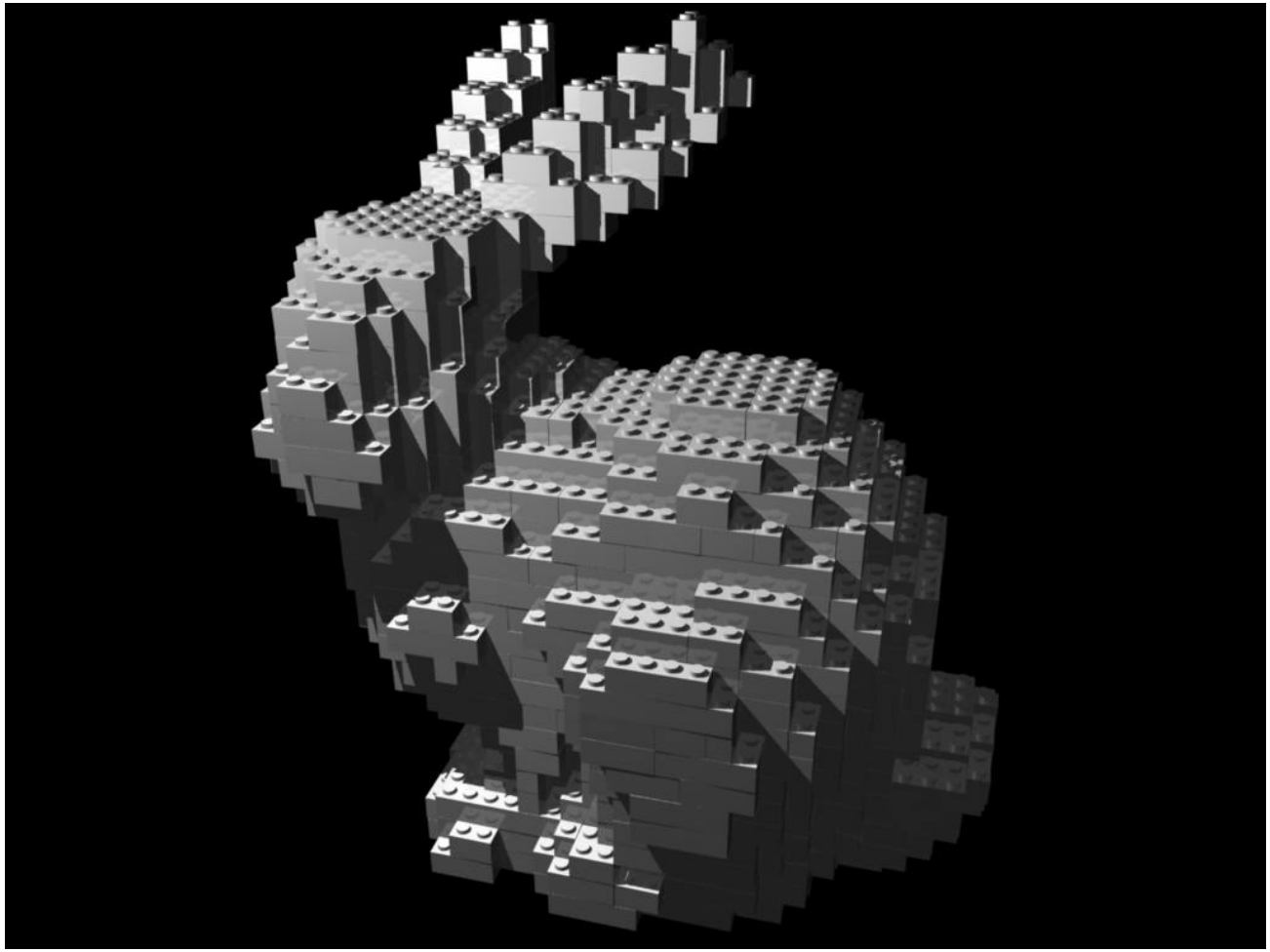
Bauul



Beachball



Bunny



Construction Plans

- Use a program called `LPub`
- Insert step meta-commands between each X-Z slice
- Example plans
- Some reworking done during build

References

References

"A Fast Depth-Buffer-Based Voxelization Algorithm" Evaggelia-Aggeliki Karabassi, Georgios Papaioannou, and Theoharis Theoharis. ACM Journal of Graphics Tools. 4(4):5-10, 1999.

LDraw website http://www.ldraw.org

"Volume Graphics" Arie Kaufman, Daniel Cohen and Roni Yagel. IEEE Computer. Vol.26, No. 7. July 1993. pg. 51-64.

Media

- All source code publically available (via CVS)
- uber: http://graphics.vr.clemson.edu
- CVS:

  http://jet.vr.clemson.edu/viewcvs/viewcvs.cgi/uber/demos/lego/?cvsroot=UBER