littlewood

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Contents

1 COPYING

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```

2 fp32_draw.frag

```
/*
    littlewood -- GPU accelerated Littlewood fractal renderer
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*/
#version 330 core
precision highp float;

```

```
#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

in block {
  vec4 Color;
} In;

layout(location = FRAG_COLOR, index = 0) out vec4 Color;

void main() {
  Color = In.Color;
}
```

3 fp32_draw.vert

```
/*
    littlewood -- GPU accelerated Littlewood fractal renderer
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*/
#version 330 core
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

uniform mat4 MVP;

layout(location = POSITION) in vec4 Position;
layout(location = COLOR) in vec4 Color;

out block {
  vec4 Color;
} Out;

void main() {
  gl_Position = MVP * vec4(Position.xy, 0.0, 1.0);
  float h = Color.z;
  float y = 0.5;
  float u = 0.25 * cos(h);
  float v = 0.25 * sin(h);
  Out.Color = vec4(y, u, v, 1.0);
}
```

4 fp32_init0.frag

```
/*
    littlewood -- GPU accelerated Littlewood fractal renderer
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*/
#version 330 core
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

in block {
  smooth vec4 Color;
} In;

layout(location = FRAG_COLOR, index = 0) out vec4 Color;

void main() {
  Color = In.Color;
}
```

5 fp32_init0.vert

```
/*
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*/
#version 330 core
precision highp float;
```

```
20
#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

25 uniform mat4 MVP;

layout(location = POSITION) in vec4 Position;

out block {
30   smooth vec4 Color;
} Out;

void main() {
  gl_Position = MVP * vec4(Position.xy, 0.0, 1.0);
35   Out.Color = vec4(Position.xy, 1.0, 0.0);
}
```

6 fp32_init1.geom

```
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    along with this program.  If not, see <http://www.gnu.org/licenses/>.
*/
#version 330 core
#extension GL_ARB_separate_shader_objects : enable
20 precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0
25
layout(points) in;
layout(points, max_vertices = 1) out;

layout(location = POSITION) in vec4 OutPosition[1];
30 layout(location = COLOR) in vec4 OutColor[1];

layout(location = POSITION) out vec4 Position;
layout(location = COLOR) out vec4 Color;

35 void main() {
  Position = OutPosition[0];
  Color = OutColor[0];
```

```
  EmitVertex();
  EndPrimitive();
}
```

7 fp32_init1.vert

```
/*
    littlewood -- GPU accelerated Littlewood fractal renderer
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    along with this program.  If not, see <http://www.gnu.org/licenses/>.
*/
#version 330 core
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

layout(location = POSITION) in vec4 Position;

uniform float radius;
uniform vec2 center;

layout(location = POSITION) out vec4 OutPosition;
layout(location = COLOR) out vec4 OutColor;

void main() {
  vec2 p = Position.xy;
  vec2 z = radius * p + center;
  OutPosition = vec4(z, z);
  OutColor = vec4(1.0, 0.0, 0.0, 0.0);
}
```

8 fp32_post.frag

```
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```

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*/
#version 330 core
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

layout(location = COLOR) smooth in vec4 TexCoord;

layout(location = FRAG_COLOR, index = 0) out vec4 Color;

uniform sampler2D tex;

void main() {
  vec4 c = texture2D(tex, TexCoord.xy);
  float y = c.r;
  float u = c.g;
  float v = c.b;
  if (y > 0.0) {
    float k = log2(y + 1.0) / y;
    k /= 16.0;
    y *= k;
    u *= k;
    v *= k;
  }
  vec3 rgb = vec3(y + 1.28033 * v, y - 0.21482 * u - 0.38059 * v, y + 2.12798 * u);
  Color = vec4(clamp(rgb, 0.0, 1.0), 1.0);
}
```

9 fp32_post.vert

```
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```

```
*/
#version 330 core
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

uniform mat4 MVP;

layout(location = POSITION) in vec4 Position;

layout(location = COLOR) smooth out vec4 TexCoord;

void main() {
  gl_Position = vec4(MVP * vec4(Position.xy, 0.0, 1.0));
  TexCoord = vec4(Position.xy, 0.0, 1.0);
}
```

10 fp32_step.geom

```
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    along with this program.  If not, see <http://www.gnu.org/licenses/>.
*/
#version 330 core
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

layout(points) in;
layout(points, max_vertices = 1) out;

layout(location = POSITION) in vec4 OutPosition[1];
layout(location = COLOR) in vec4 OutColor[1];

uniform float pixelSpacing;

layout(location = POSITION) out vec4 Position;
layout(location = COLOR) out vec4 Color;
```

```
void main() {
  vec2 z = OutPosition[0].xy;
  vec2 zn = OutPosition[0].zw;
  vec2 p = OutColor[0].xy;
  float r = length(z);
  float rn = length(zn);
  if (r <= 0.8 && length(p) <= rn / (1.0 - r) + pixelSpacing) {
    Position = OutPosition[0];
    Color = OutColor[0];
    EmitVertex();
    EndPrimitive();
  }
}
```

11 fp32_step.vert

```
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*/
#version 330 core
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

layout(location = POSITION) in vec4 Position;
layout(location = COLOR) in vec4 Color;

layout(location = POSITION) out vec4 OutPosition;
layout(location = COLOR) out vec4 OutColor;

uniform float plusMinus;
uniform float hueShift;

void main() {
  vec2 z = Position.xy;
  vec2 zn = Position.zw;
  vec2 p = Color.xy;
  float h = Color.z;
  p += plusMinus * zn;
```

```
  h += hueShift;
  zn = vec2(z.x * zn.x - z.y * zn.y, z.x * zn.y + z.y * zn.x);
  OutPosition = vec4(z, zn);
  OutColor = vec4(p, h, 0.0);
}
```

12 fp64_draw.frag

```
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*/
#version 400 core
#extension GL_ARB_vertex_attrib_64bit : enable
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

in block {
  vec4 Color;
} In;

layout(location = FRAG_COLOR, index = 0) out vec4 Color;

void main() {
  Color = In.Color;
}
```

13 fp64_draw.vert

```
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*/
#version 400 core
#extension GL_ARB_vertex_attrib_64bit : enable
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

uniform dmat4 MVP;

layout(location = POSITION) in dvec4 Position;
layout(location = COLOR) in dvec4 Color;

out block {
  vec4 Color;
} Out;

void main() {
  gl_Position = vec4(MVP * dvec4(Position.xy, 0.0, 1.0));
  float h = float(Color.z);
  float y = 0.5;
  float u = 0.25 * cos(h);
  float v = 0.25 * sin(h);
  Out.Color = vec4(y, u, v, 1.0);
}
```

14 fp64_init0.frag

```
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*/
#version 400 core
#extension GL_ARB_vertex_attrib_64bit : enable
#extension GL_ARB_separate_shader_objects : enable
precision highp float;
```

```
#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

in block {
  smooth vec4 Color;
} In;

layout(location = FRAG_COLOR, index = 0) out vec4 Color;

void main() {
  Color = In.Color;
}
```

15 fp64_init0.vert

```
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*/
#version 400 core
#extension GL_ARB_vertex_attrib_64bit : enable
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

uniform dmat4 MVP;

layout(location = POSITION) in vec4 Position;

out block {
  vec4 Color;
} Out;

void main() {
  gl_Position = mat4(MVP) * vec4(Position.xy, 0.0, 1.0);
  Out.Color = vec4(Position.xy, 1.0, 0.0);
}
```

16 fp64_init1.geom

```
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*/
#version 400 core
#extension GL_ARB_vertex_attrib_64bit : enable
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

layout(points) in;
layout(points, max_vertices = 1) out;

layout(location = POSITION) in dvec4 OutPosition[1];
layout(location = COLOR) in dvec4 OutColor[1];

layout(location = POSITION) out dvec4 Position;
layout(location = COLOR) out dvec4 Color;

void main() {
  Position = OutPosition[0];
  Color = OutColor[0];
  EmitVertex();
  EndPrimitive();
}
```

17 fp64_init1.vert

```
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```
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    */
    #version 400 core
    #extension GL_ARB_vertex_attrib_64bit : enable
20  #extension GL_ARB_separate_shader_objects : enable
    precision highp float;

    #define POSITION        0
    #define COLOR           3
25  #define FRAG_COLOR      0

    layout(location = POSITION) in vec4 Position;

    uniform double radius;
30  uniform dvec2 center;

    out block {
    layout(location = POSITION) dvec4 Position;
    layout(location = COLOR) dvec4 Color;
35  } Out;

    void main() {
      vec2 p = Position.xy;
      dvec2 z = radius * dvec2(p) + center;
40    Out.Position = dvec4(z, z);
      Out.Color = dvec4(1.0, 0.0, 0.0, 0.0);
    }
```

18 fp64_post.frag

```
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    */
    #version 400 core
    #extension GL_ARB_vertex_attrib_64bit : enable
20  #extension GL_ARB_separate_shader_objects : enable
    precision highp float;

    #define POSITION        0
    #define COLOR           3
25  #define FRAG_COLOR      0
```

```
in block {
  layout(location = COLOR) smooth vec4 TexCoord;
} In;

layout(location = FRAG_COLOR, index = 0) out vec4 Color;

uniform sampler2D tex;

void main() {
  vec4 c = texture2D(tex, In.TexCoord.xy);
  float y = c.r;
  float u = c.g;
  float v = c.b;
  if (y > 0.0) {
    float k = log2(y + 1.0) / y;
    k /= 16.0;
    y *= k;
    u *= k;
    v *= k;
  }
  vec3 rgb = vec3(y + 1.28033 * v, y - 0.21482 * u - 0.38059 * v, y + 2.12798 * u);
  Color = vec4(clamp(rgb, 0.0, 1.0), 1.0);
}
```

19 fp64_post.vert

```
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*/
#version 400 core
#extension GL_ARB_vertex_attrib_64bit : enable
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

uniform dmat4 MVP;

layout(location = POSITION) in vec4 Position;
```

```
30
out block {
  layout(location = COLOR) vec4 TexCoord;
} Out;

35 void main() {
  gl_Position = vec4(mat4(MVP) * vec4(Position.xy, 0.0, 1.0));
  Out.TexCoord = vec4(Position.xy, 0.0, 1.0);
}
```

20 fp64_step.geom

```
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*/
#version 400 core
#extension GL_ARB_vertex_attrib_64bit : enable
20 #extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
25 #define FRAG_COLOR      0

layout(points) in;
layout(points, max_vertices = 1) out;

30 layout(location = POSITION) in dvec4 OutPosition[1];
layout(location = COLOR) in dvec4 OutColor[1];

uniform double pixelSpacing;

35 layout(location = POSITION) out dvec4 Position;
layout(location = COLOR) out dvec4 Color;

void main() {
  dvec2 z = OutPosition[0].xy;
40  dvec2 zn = OutPosition[0].zw;
  dvec2 p = OutColor[0].xy;
  double r = length(z);
  double rn = length(zn);
  if (r <= 0.8 && length(p) <= rn / (1.0 - r) + pixelSpacing) {
45    Position = OutPosition[0];
```

```
    Color = OutColor[0];
    EmitVertex();
    EndPrimitive();
  }
}
```

21 fp64_step.vert

```
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*/
#version 400 core
#extension GL_ARB_vertex_attrib_64bit : enable
#extension GL_ARB_separate_shader_objects : enable
precision highp float;

#define POSITION        0
#define COLOR           3
#define FRAG_COLOR      0

layout(location = POSITION) in dvec4 Position;
layout(location = COLOR) in dvec4 Color;

out block {
layout(location = POSITION)   dvec4 Position;
layout(location = COLOR)   dvec4 Color;
} Out;

uniform double plusMinus;
uniform double hueShift;

void main() {
  dvec2 z = Position.xy;
  dvec2 zn = Position.zw;
  dvec2 p = Color.xy;
  double h = Color.z;
  p += plusMinus * zn;
  h += hueShift;
  zn = dvec2(z.x * zn.x - z.y * zn.y, z.x * zn.y + z.y * zn.x);
  Out.Position = dvec4(z, zn);
  Out.Color = dvec4(p, h, 0.0);
}
```

22 .gitignore

```
littlewood-fp32
littlewood-fp64
*.c
```

23 littlewood.cc

```
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*/

#ifndef FP
#define FP 32
#endif

#include <GL/glew.h>
#include <GL/freeglut.h>

#include <stdio.h>
#include <time.h>

#include <glm/glm.hpp>
#include <glm/gtc/matrix_transform.hpp>

#if (FP == 32)

#include "fp32_init0.vert.c"
static const char *init0_vert = fp32_init0_vert;
#include "fp32_init0.frag.c"
static const char *init0_frag = fp32_init0_frag;
#include "fp32_init1.vert.c"
static const char *init1_vert = fp32_init1_vert;
#include "fp32_init1.geom.c"
static const char *init1_geom = fp32_init1_geom;
#include "fp32_step.vert.c"
static const char *step_vert = fp32_step_vert;
#include "fp32_step.geom.c"
static const char *step_geom = fp32_step_geom;
#include "fp32_draw.vert.c"
static const char *draw_vert = fp32_draw_vert;
#include "fp32_draw.frag.c"
static const char *draw_frag = fp32_draw_frag;
```

```
#include "fp32_post.vert.c"
static const char *post_vert = fp32_post_vert;
#include "fp32_post.frag.c"
static const char *post_frag = fp32_post_frag;

static const int major = 3;
static const int minor = 3;
typedef glm::vec4 vec4;
typedef glm::mat4 mat4;
typedef float flt;
#define glVertexAttribPointer_(a,b,c,d,e) glVertexAttribPointer(a,b,GL_FLOAT,c,d,e)
#define glUniformMatrix4fv_ glUniformMatrix4fv
#define glUniform1f_ glUniform1f
#define glUniform2f_ glUniform2f
#define glVertex2f_ glVertex2f

#else
#if (FP == 64)

#include "fp64_init0.vert.c"
static const char *init0_vert = fp64_init0_vert;
#include "fp64_init0.frag.c"
static const char *init0_frag = fp64_init0_frag;
#include "fp64_init1.vert.c"
static const char *init1_vert = fp64_init1_vert;
#include "fp64_init1.geom.c"
static const char *init1_geom = fp64_init1_geom;
#include "fp64_step.vert.c"
static const char *step_vert = fp64_step_vert;
#include "fp64_step.geom.c"
static const char *step_geom = fp64_step_geom;
#include "fp64_draw.vert.c"
static const char *draw_vert = fp64_draw_vert;
#include "fp64_draw.frag.c"
static const char *draw_frag = fp64_draw_frag;
#include "fp64_post.vert.c"
static const char *post_vert = fp64_post_vert;
#include "fp64_post.frag.c"
static const char *post_frag = fp64_post_frag;

static const int major = 4;
static const int minor = 0;
typedef glm::dvec4 vec4;
typedef glm::dmat4 mat4;
typedef double flt;
#define glVertexAttribPointer_(a,b,c,d,e) glVertexAttribLPointer(a,b,GL_DOUBLE,d,e)
#define glUniformMatrix4fv_ glUniformMatrix4dv
#define glUniform1f_ glUniform1d
#define glUniform2f_ glUniform2d
#define glVertex2f_ glVertex2d

#else
#error unknown precision (expected 32 or 64)

#endif
```

```
105 #endif

    #define pi 3.141592653589793
    #define BUFFER_OFFSET(i) (((unsigned char *)0)+i)
    #define POSITION 0
110 #define COLOR 3
    struct point { vec4 pos, col; };

    #define D do{ int e = glGetError(); if (e != 0) { fprintf(stderr, "OpenGL error ↙
        ↳ %d in %s() (line %d)\n", e, __FUNCTION__, __LINE__); } }while(0)

115 static const int tex_width = 512;
    static const int tex_height = 512;

    static int win_width = 512;
    static int win_height = 512;
120
    static GLsizei const VertexCount(1 << 24);

    static flt cx = 0;
    static flt cy = 0;
125 static flt r  = 1;
    static mat4 MVP;

    static int which = 0;
    static GLuint PingPongArrayBufferName[2];
130 static GLuint PingPongVertexArrayName[2];
    static GLuint InitVertexArrayName(0);

    static GLuint InitVBO(0);
    static GLuint InitVAO(0);
135
    static GLuint PostVBO(0);
    static GLuint PostVAO(0);

    static GLuint Init0ProgramName(0);
140 static GLint  Init0UniformMVP(0);

    static GLuint Init1ProgramName(0);
    static GLint  Init1UniformCenter(0);
    static GLint  Init1UniformRadius(0);
145
    static GLuint StepProgramName(0);
    static GLint  StepUniformPlusMinus(0);
    static GLint  StepUniformHueShift(0);
    static GLint  StepUniformPixelSpacing(0);
150
    static GLuint DrawProgramName(0);
    static GLint  DrawUniformMVP(0);

    static GLuint PostProgramName(0);
155 static GLint  PostUniformMVP(0);
    static GLint  PostUniformTex(0);

    static GLuint Texture2DName(0);
    static GLuint FramebufferName(0);
160
```

```
static GLuint Query(0);

static GLuint createShader(GLenum Type, const GLchar *Source) {
  GLuint Name = glCreateShader(Type);
  glShaderSource(Name, 1, &Source, NULL);
  glCompileShader(Name);
  return Name;
}

static bool checkProgram(GLuint ProgramName, const char *header) {
  if (!ProgramName) {
    return false;
  }
  GLint Result = GL_FALSE;
  glGetProgramiv(ProgramName, GL_LINK_STATUS, &Result);
  if (Result != GL_TRUE) {
    fprintf(stderr, "%s: link failed\n", header);
  }
  int InfoLogLength;
  glGetProgramiv(ProgramName, GL_INFO_LOG_LENGTH, &InfoLogLength);
  char *Buffer = (char *) malloc(InfoLogLength + 1); {
    glGetProgramInfoLog(ProgramName, InfoLogLength, NULL, &Buffer[0]);
    Buffer[InfoLogLength] = 0;
    if (Buffer[0]) {
      fprintf(stderr, "%s:\n%s\n", header, &Buffer[0]);
    }
  } free(Buffer);
  return Result == GL_TRUE;
}

static bool initProgram() {
  bool Validated = true;
  // Create program 'init0'
  {
    GLuint VertexShaderName = createShader(GL_VERTEX_SHADER, init0_vert);D;
    GLuint FragmentShaderName = createShader(GL_FRAGMENT_SHADER, init0_frag);D;
    Init0ProgramName = glCreateProgram();D;
    glAttachShader(Init0ProgramName, VertexShaderName);D;
    glAttachShader(Init0ProgramName, FragmentShaderName);D;
    glDeleteShader(VertexShaderName);D;
    glDeleteShader(FragmentShaderName);D;
    glLinkProgram(Init0ProgramName);D;
    Validated = Validated && checkProgram(Init0ProgramName, "init0");
    Init0UniformMVP = glGetUniformLocation(Init0ProgramName, "MVP");D;
    Validated = Validated && Init0UniformMVP != -1;
  }
  // Create program 'init1'
  {
    GLuint VertexShaderName = createShader(GL_VERTEX_SHADER, init1_vert);D;
    GLuint GeometryShaderName = createShader(GL_GEOMETRY_SHADER, init1_geom);D;
    Init1ProgramName = glCreateProgram();D;
    glAttachShader(Init1ProgramName, VertexShaderName);D;
    glAttachShader(Init1ProgramName, GeometryShaderName);D;
    glDeleteShader(VertexShaderName);D;
    glDeleteShader(GeometryShaderName);D;
    GLchar const * Strings[] = {"Position", "Color"};
    glTransformFeedbackVaryings(Init1ProgramName, 2, Strings, ↙
```

```
        ↳ GL_INTERLEAVED_ATTRIBS);D;
      glLinkProgram(Init1ProgramName);D;
      Validated = Validated && checkProgram(Init1ProgramName, "init1");
      Init1UniformCenter = glGetUniformLocation(Init1ProgramName, "center");D;
      Init1UniformRadius = glGetUniformLocation(Init1ProgramName, "radius");D;
      Validated = Validated && Init1UniformCenter != -1 && Init1UniformRadius != ↙
        ↳ -1;
    }
    // Create program 'step'
    {
      GLuint VertexShaderName = createShader(GL_VERTEX_SHADER, step_vert);D;
      GLuint GeometryShaderName = createShader(GL_GEOMETRY_SHADER, step_geom);D;
      StepProgramName = glCreateProgram();D;
      glAttachShader(StepProgramName, VertexShaderName);D;
      glAttachShader(StepProgramName, GeometryShaderName);D;
      glDeleteShader(VertexShaderName);D;
      glDeleteShader(GeometryShaderName);D;
      GLchar const * Strings[] = {"Position", "Color"};
      glTransformFeedbackVaryings(StepProgramName, 2, Strings, ↙
        ↳ GL_INTERLEAVED_ATTRIBS);D;
      glLinkProgram(StepProgramName);D;
      Validated = Validated && checkProgram(StepProgramName, "step");
      StepUniformPlusMinus = glGetUniformLocation(StepProgramName, "plusMinus");D;
      StepUniformHueShift = glGetUniformLocation(StepProgramName, "hueShift");D;
      StepUniformPixelSpacing = glGetUniformLocation(StepProgramName, "↙
        ↳ pixelSpacing");D;
      Validated = Validated && StepUniformPlusMinus != -1 && StepUniformHueShift ↙
        ↳ != -1 && StepUniformPixelSpacing != -1;
    }
    // Create program 'draw'
    {
      GLuint VertexShaderName = createShader(GL_VERTEX_SHADER, draw_vert);D;
      GLuint FragmentShaderName = createShader(GL_FRAGMENT_SHADER, draw_frag);D;
      DrawProgramName = glCreateProgram();D;
      glAttachShader(DrawProgramName, VertexShaderName);D;
      glAttachShader(DrawProgramName, FragmentShaderName);D;
      glDeleteShader(VertexShaderName);D;
      glDeleteShader(FragmentShaderName);D;
      glLinkProgram(DrawProgramName);D;
      Validated = Validated && checkProgram(DrawProgramName, "draw");
      DrawUniformMVP = glGetUniformLocation(DrawProgramName, "MVP");D;
      Validated = Validated && DrawUniformMVP != -1;
    }
    // Create program 'post'
    {
      GLuint VertexShaderName = createShader(GL_VERTEX_SHADER, post_vert);D;
      GLuint FragmentShaderName = createShader(GL_FRAGMENT_SHADER, post_frag);D;
      PostProgramName = glCreateProgram();D;
      glAttachShader(PostProgramName, VertexShaderName);D;
      glAttachShader(PostProgramName, FragmentShaderName);D;
      glDeleteShader(VertexShaderName);D;
      glDeleteShader(FragmentShaderName);D;
      glLinkProgram(PostProgramName);D;
      Validated = Validated && checkProgram(PostProgramName, "post");
      PostUniformMVP = glGetUniformLocation(PostProgramName, "MVP");D;
      PostUniformTex = glGetUniformLocation(PostProgramName, "tex");D;
      Validated = Validated && PostUniformMVP != -1 && PostUniformTex != -1;
```

```
270     }
        return Validated;
      }

      static void initVertexArray1(GLuint *name, GLuint arr) {
275     glGenVertexArrays(1, name);D;
        glBindVertexArray(*name);D; {
          glBindBuffer(GL_ARRAY_BUFFER, arr);D; {
            glVertexAttribPointer_(POSITION, 4, GL_FALSE, sizeof(point), 0);D;
          } glBindBuffer(GL_ARRAY_BUFFER, 0);D;
280       glBindBuffer(GL_ARRAY_BUFFER, arr);D; {
            glVertexAttribPointer_(COLOR, 4, GL_FALSE, sizeof(point), BUFFER_OFFSET(↙
                ↳ sizeof(vec4)));D;
          } glBindBuffer(GL_ARRAY_BUFFER, 0);D;
          glEnableVertexAttribArray(POSITION);D;
          glEnableVertexAttribArray(COLOR);D;
285     } glBindVertexArray(0);D;
      }

      static void initVertexArray() {
        initVertexArray1(&PingPongVertexArrayName[0], PingPongArrayBufferName[0]);D;
290     initVertexArray1(&PingPongVertexArrayName[1], PingPongArrayBufferName[1]);D;
        glGenVertexArrays(1, &InitVertexArrayName);D;
        glBindVertexArray(InitVertexArrayName);D; {
          glBindBuffer(GL_ARRAY_BUFFER, PingPongArrayBufferName[1]);D; {
            glVertexAttribPointer(POSITION, 4, GL_FLOAT, GL_FALSE, sizeof(glm::vec4), ↙
                ↳ 0);D;
295       } glBindBuffer(GL_ARRAY_BUFFER, 0);D;
          glEnableVertexAttribArray(POSITION);D;
        } glBindVertexArray(0);D;
      }

300   static void initArrayBuffer1(GLuint *name) {
        glGenBuffers(1, name);D;
        glBindBuffer(GL_ARRAY_BUFFER, *name);D; {
          glBufferData(GL_ARRAY_BUFFER, sizeof(point) * VertexCount, NULL, ↙
              ↳ GL_DYNAMIC_COPY);D;
        } glBindBuffer(GL_ARRAY_BUFFER, 0);D;
305   }

      static GLuint resetView() {
        which = 0;
        fprintf(stderr, "%+.16g + %+.16g i @ %g (%d)\t", cx, cy, r, int(-log2(r)));
310     GLuint active2;
        GLuint active = win_width * win_height;
        if (active > 0) {
          // Set the display viewport
          flt a = flt(win_width) / flt(win_height);
315       MVP = glm::ortho(-a, a, flt(-1), flt(1));
          glBindFramebuffer(GL_FRAMEBUFFER, FramebufferName);D; {
            glViewport(0, 0, win_width, win_height);D;
            glUseProgram(Init0ProgramName);D; {
              glUniformMatrix4fv_(Init0UniformMVP, 1, GL_FALSE, &MVP[0][0]);D;
320           glBindVertexArray(InitVAO);D; {
                glBindBuffer(GL_ARRAY_BUFFER, InitVBO);D; {
                  GLfloat v[8] = { GLfloat(-a), -1, GLfloat(a), -1, GLfloat(-a), 1, ↙
                      ↳ GLfloat(a), 1 };
```

```
            glBufferSubData(GL_ARRAY_BUFFER, 0, sizeof(v), v);D;
            glDrawArrays(GL_TRIANGLE_STRIP, 0, 4);D;
          } glBindBuffer(GL_ARRAY_BUFFER, 0);D;
        } glBindVertexArray(0);D;
      } glUseProgram(0);D;
      // copy to Pong
      glBindBuffer(GL_PIXEL_PACK_BUFFER, PingPongArrayBufferName[1]);D; {
        glReadPixels(0, 0, win_width, win_height, GL_RGBA, GL_FLOAT, 0);D;
      } glBindBuffer(GL_PIXEL_PACK_BUFFER, 0);D;
    } glBindFramebuffer(GL_FRAMEBUFFER, 0);D;
    // transform to Ping
    glEnable(GL_RASTERIZER_DISCARD);D; {
      glUseProgram(Init1ProgramName);D; {
        glUniform1f_(Init1UniformRadius, r);D;
        glUniform2f_(Init1UniformCenter, cx, cy);D;
        glBindVertexArray(InitVertexArrayName);D; {
          glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, ↙
              ↳ PingPongArrayBufferName[0]);D; {
            glBeginQuery(GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN, Query);D; {
              glBeginTransformFeedback(GL_POINTS);D; {
                glDrawArrays(GL_POINTS, 0, active);D;
              } glEndTransformFeedback();D;
            } glEndQuery(GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN);D;
            glGetQueryObjectuiv(Query, GL_QUERY_RESULT, &active2);D;
          } glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, 0);D;
        } glBindVertexArray(0);D;
      } glUseProgram(0);D;
    } glDisable(GL_RASTERIZER_DISCARD);D;
  }
  return active;
}

static void initArrayBuffer() {
  initArrayBuffer1(&PingPongArrayBufferName[0]);D;
  initArrayBuffer1(&PingPongArrayBufferName[1]);D;
}

static int calculate1(GLuint active, int pass) {
  if (active <= 0) return 0;
  GLuint kept1 = 0;
  GLuint kept2 = 0;
  glEnable(GL_RASTERIZER_DISCARD);D; {
    glUseProgram(StepProgramName);D; {
      glUniform1f_(StepUniformPixelSpacing, r * sqrt(2.0) / win_height);D;
      glBindVertexArray(PingPongVertexArrayName[which]);D; {

        glUniform1f_(StepUniformPlusMinus,   1);D;
        glUniform1f_(StepUniformHueShift,    pi * pow(0.5, pass + 1));D;
        glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, ↙
            ↳ PingPongArrayBufferName[1 - which]);D; {
          glBeginQuery(GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN, Query);D; {
            glBeginTransformFeedback(GL_POINTS);D; {
              glDrawArrays(GL_POINTS, 0, active);D;
            } glEndTransformFeedback();D;
              } glEndQuery(GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN);D;
              glGetQueryObjectuiv(Query, GL_QUERY_RESULT, &kept1);D;
        } glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, 0);D;
```

```
          glUniform1f_(StepUniformPlusMinus, -1);D;
380       glUniform1f_(StepUniformHueShift, -pi * pow(0.5, pass + 1));D;
          glBindBufferRange(GL_TRANSFORM_FEEDBACK_BUFFER, 0, ↙
              ↳ PingPongArrayBufferName[1 - which], kept1 * sizeof(point), (↙
              ↳ VertexCount - kept1) * sizeof(point));D; {
            glBeginQuery(GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN, Query);D; {
              glBeginTransformFeedback(GL_POINTS);D; {
                glDrawArrays(GL_POINTS, 0, active);D;
385           } glEndTransformFeedback();D;
            } glEndQuery(GL_TRANSFORM_FEEDBACK_PRIMITIVES_WRITTEN);D;
            glGetQueryObjectuiv(Query, GL_QUERY_RESULT, &kept2);D;
          } glBindBufferBase(GL_TRANSFORM_FEEDBACK_BUFFER, 0, 0);D;

390     } glBindVertexArray(0);D;
      } glUseProgram(0);
      which = 1 - which;
    } glDisable(GL_RASTERIZER_DISCARD);D;
    return kept1 + kept2;
395 }

    static void draw(GLuint active) {
      flt a = flt(win_width) / flt(win_height);
      MVP = glm::ortho(cx - a * r, cx + a * r, cy - r, cy + r);
400   glViewport(0, 0, win_width, win_height);D;
      glEnable(GL_BLEND);D; {
        glBlendFunc(GL_SRC_ALPHA, GL_ONE);D;
        glUseProgram(DrawProgramName);D; {
          glUniformMatrix4fv_(DrawUniformMVP, 1, GL_FALSE, &MVP[0][0]);D;
405       glBindVertexArray(PingPongVertexArrayName[which]);D; {
            glDrawArrays(GL_POINTS, 0, active);D;
          } glBindVertexArray(0);D;
        } glUseProgram(0);D;
      } glDisable(GL_BLEND);D;
410 }

    static GLuint calculate(GLuint active) {
      int pass = 0;
      while (2 * active <= GLuint(VertexCount) && pass < 256) {
415     active = calculate1(active, pass);
        pass += 1;
      }
      fprintf(stderr, "%9d\t%d\t", active, pass);
      return active;
420 }

    static void render() {
      GLuint active = 0;
      active = resetView();
425   active = calculate(active);
      glBindFramebuffer(GL_FRAMEBUFFER, FramebufferName);D; {
        glClear(GL_COLOR_BUFFER_BIT);
        draw(active);
      } glBindFramebuffer(GL_FRAMEBUFFER, 0);D;
430   flt x = flt(win_width  - 1) / flt(tex_width);
      flt y = flt(win_height - 1) / flt(tex_height);
      MVP = glm::ortho(flt(0), x, flt(0), y);
```

```
  glUseProgram(PostProgramName);D; {
    glBindTexture(GL_TEXTURE_2D, Texture2DName);D; {
      glUniformMatrix4fv_(PostUniformMVP, 1, GL_FALSE, &MVP[0][0]);D;
      glUniform1i(PostUniformTex, 0);D;
      glBindVertexArray(PostVAO);D; {
        glBindBuffer(GL_ARRAY_BUFFER, PostVBO);D; {
          GLfloat v[8] = { 0, 0, GLfloat(x), 0, 0, GLfloat(y), GLfloat(x), ↙
              ↘ GLfloat(y) };
          glBufferSubData(GL_ARRAY_BUFFER, 0, sizeof(v), v);D;
          glDrawArrays(GL_TRIANGLE_STRIP, 0, 4);D;
        } glBindBuffer(GL_ARRAY_BUFFER, 0);D;
      } glBindVertexArray(0);D;
    } glBindTexture(GL_TEXTURE_2D, 0);D;
  } glUseProgram(0);D;
  glutSwapBuffers();
}

static bool begincb() {
  bool Validated = true;
  // glClampColor(GL_CLAMP_VERTEX_COLOR, GL_FALSE);D;
  glClampColor(GL_CLAMP_READ_COLOR, GL_FALSE);D;
  // glClampColor(GL_CLAMP_FRAGMENT_COLOR, GL_FALSE);D;

  glGenQueries(1, &Query);D;
  Validated = Validated && initProgram();
  initArrayBuffer();
  initVertexArray();

  glGenBuffers(1, &PostVBO);D;
  glGenVertexArrays(1, &PostVAO);D;
  glBindVertexArray(PostVAO);D; {
    glBindBuffer(GL_ARRAY_BUFFER, PostVBO);D; {
      glBufferData(GL_ARRAY_BUFFER, 8 * sizeof(GLfloat), 0, GL_DYNAMIC_DRAW);D;
      glVertexAttribPointer(POSITION, 2, GL_FLOAT, GL_FALSE, 0, 0);D;
      glEnableVertexAttribArray(POSITION);D;
    } glBindBuffer(GL_ARRAY_BUFFER, 0);D;
  } glBindVertexArray(0);D;
  glGenBuffers(1, &InitVBO);D;
  glGenVertexArrays(1, &InitVAO);D;
  glBindVertexArray(InitVAO);D; {
    glBindBuffer(GL_ARRAY_BUFFER, InitVBO);D; {
      glBufferData(GL_ARRAY_BUFFER, 8 * sizeof(GLfloat), 0, GL_DYNAMIC_DRAW);D;
      glVertexAttribPointer(POSITION, 2, GL_FLOAT, GL_FALSE, 0, 0);D;
      glEnableVertexAttribArray(POSITION);D;
    } glBindBuffer(GL_ARRAY_BUFFER, 0);D;
  } glBindVertexArray(0);D;

  glGenTextures(1, &Texture2DName);D;
  glBindTexture(GL_TEXTURE_2D, Texture2DName);D;
  glTexImage2D(GL_TEXTURE_2D, 0, GL_RGBA32F, tex_width, tex_height, 0, GL_RGBA, ↙
      ↘ GL_UNSIGNED_BYTE, 0);D;
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_NEAREST);
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_NEAREST);
  glBindTexture(GL_TEXTURE_2D, 0);D;
  glGenFramebuffers(1, &FramebufferName);D;
  glBindFramebuffer(GL_FRAMEBUFFER, FramebufferName);D;
  glFramebufferTexture2D(GL_FRAMEBUFFER, GL_COLOR_ATTACHMENT0, GL_TEXTURE_2D, ↙
```

```
      ↪ Texture2DName, 0);D;
    GLenum DrawBuffers[1] = { GL_COLOR_ATTACHMENT0 };
    glDrawBuffers(1, DrawBuffers);D;
    if (glCheckFramebufferStatus(GL_FRAMEBUFFER) != GL_FRAMEBUFFER_COMPLETE) {
      fprintf(stderr, "frame buffer %d\n", glCheckFramebufferStatus(GL_FRAMEBUFFER↙
          ↪ ));
    }
    glBindFramebuffer(GL_FRAMEBUFFER, 0);D;
    return Validated;
}

static void endcb() {
  // FIXME clean up gracefully!
  // glDeleteVertexArrays(1, &va);
  // glDeleteBuffers(1, &ab);
  // glDeleteProgram(p);
  // glDeleteQueries(1, &q);
}

static void displaycb(void) {
  clock_t start = clock();
  glClear(GL_COLOR_BUFFER_BIT);
  render();
  clock_t end = clock();
  double elapsed = 1000.0 * ((double) (end - start)) / CLOCKS_PER_SEC;
  fprintf(stderr, "%dms\n", int(elapsed));
  glutSwapBuffers();
}

static void reshapecb(int w, int h) {
  if (w > tex_width || h > tex_height) {
    fprintf(stderr, "warning: window size too big\n");
  }
  win_width = w;
  win_height = h;
  glutPostRedisplay();
}

static void mousecb(int button, int state, int x, int y) {
  if (state == GLUT_DOWN) {
    if (button == GLUT_LEFT_BUTTON) {
      cx += 2 * r * (x -  win_width / 2.0) / win_height;
      cy += 2 * r * (win_height / 2.0 - y) / win_height;
      r  *= 0.5;
      glutPostRedisplay();
    } else if (button == GLUT_MIDDLE_BUTTON) {
      cx += 2 * r * (x -  win_width / 2.0) / win_height;
      cy += 2 * r * (win_height / 2.0 - y) / win_height;
      r  *= 1.0;
      glutPostRedisplay();
    } else if (button == GLUT_RIGHT_BUTTON) {
      cx += 2 * r * (x -  win_width / 2.0) / win_height;
      cy += 2 * r * (win_height / 2.0 - y) / win_height;
      r  *= 2.0;
      glutPostRedisplay();
    }
  }
```

```
}

static void keyboardcb(unsigned char key, int x, int y) {
  (void) x;
  (void) y;
  if (key == 27) {
    exit(0);
  }
}

static void closecb() {
  exit(0);
}

int main(int argc, char* argv[]) {
  glutInitWindowSize(win_width, win_height);
  glutInit(&argc, argv);
  glutInitDisplayMode(GLUT_RGBA | GLUT_DOUBLE);

  int WindowHandle = glutCreateWindow(argv[0]);
  glewInit();
  glutDestroyWindow(WindowHandle);

  glutInitContextVersion(major, minor);
  if (100 * major + 10 * minor >= 320) {
//    glutInitContextProfile(GLUT_COMPATIBILITY_PROFILE);
    glutInitContextFlags(GLUT_FORWARD_COMPATIBLE | GLUT_DEBUG);
  }
  glutCreateWindow(argv[0]);

  if (! begincb()) { return 1; }

  glutDisplayFunc(displaycb);
  glutReshapeFunc(reshapecb);
  glutMouseFunc(mousecb);
  glutKeyboardFunc(keyboardcb);
  glutCloseFunc(closecb);
  atexit(endcb);
  glutMainLoop();
  return 0;
}
```

24 Makefile

```
#
#   littlewood -- GPU accelerated Littlewood fractal renderer
#   Copyright (C) 2012,2015,2017  Claude Heiland-Allen <claude@mathr.co.uk>
#
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```

```
#
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#

LIBS = -lGLEW -lglut -lGL
CCFLAGS = -Wall -pedantic -Wextra -O3 -march=native -ggdb

all: littlewood-fp32 littlewood-fp64

clean:
	-rm littlewood-fp32 fp32_init0.frag.c fp32_init0.vert.c fp32_init1.geom.c fp32_init1.vert.c fp32_step.geom.c fp32_step.vert.c fp32_draw.frag.c fp32_draw.vert.c fp32_post.frag.c fp32_post.vert.c
	-rm littlewood-fp64 fp64_init0.frag.c fp64_init0.vert.c fp64_init1.geom.c fp64_init1.vert.c fp64_step.geom.c fp64_step.vert.c fp64_draw.frag.c fp64_draw.vert.c fp64_post.frag.c fp64_post.vert.c

.SUFFIXES:
.PHONY: all clean

littlewood-fp32: littlewood.cc fp32_init0.frag.c fp32_init0.vert.c fp32_init1.geom.c fp32_init1.vert.c fp32_step.geom.c fp32_step.vert.c fp32_draw.frag.c fp32_draw.vert.c fp32_post.frag.c fp32_post.vert.c
	g++ $(CCFLAGS) -DFP=32 -o littlewood-fp32 littlewood.cc $(LIBS)

littlewood-fp64: littlewood.cc fp64_init0.frag.c fp64_init0.vert.c fp64_init1.geom.c fp64_init1.vert.c fp64_step.geom.c fp64_step.vert.c fp64_draw.frag.c fp64_draw.vert.c fp64_post.frag.c fp64_post.vert.c
	g++ $(CCFLAGS) -DFP=64 -o littlewood-fp64 littlewood.cc $(LIBS)

# shader source to C source

%.frag.c: %.frag s2c.sh
	./s2c.sh $*_frag < $< > $@

%.geom.c: %.geom s2c.sh
	./s2c.sh $*_geom < $< > $@

%.vert.c: %.vert s2c.sh
	./s2c.sh $*_vert < $< > $@
```

25 README

```
littlewood -- GPU accelerated Littlewood fractal renderer
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```
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15  along with this program.  If not, see <http://www.gnu.org/licenses/>.


    littlewood requires freeglut, glew, glm
    littlewood-fp32 requires OpenGL 3.3
20  littlewood-fp64 requires OpenGL 4.0

    left-click to zoom in
    middle-click to center
    right-click to zoom out
25  esc to quit

    viewport parameters and statistics are printed on stderr:
    centerx centery radiusy -log2(radiusy) roots order time

30
    data flow:
        viewing parameters
    ->  init0 shader generates coordinates                    } float32
    ->  stored in framebuffer texture                         }
35  ->  copy to vertex buffer                                 }
    ->  init1 shader augments coordinates with initial state  } floatNN
      loop until vertex buffer could overflow:                }
      ->  ping vertex buffer                                  }
      ->  step shader (twice, once with + and once with -)    }
40    ->  pong vertex buffer                                  }
      ->  swap(ping, pong)                                    }
    ->  draw shader accumulates points in framebuffer texture } float32
    ->  post shader normalizes colour range                   }
    ->  output image                                          } uint8
45

    could possibly be described as an approximantion to infinite-order
    algorithm prunes polynomials that can't converge to 0 anywhere in the pixel
    if a pixel is black, there is for sure no root nearby
50  pixel brightness is related to number of paths that haven't been pruned
    pixel colour is related to the choices made at each step (+/-)


    references:
55  http://www.gregegan.net/SCIENCE/Littlewood/Littlewood.html
    http://johncarlosbaez.wordpress.com/2011/12/11/the-beauty-of-roots/
      (search comments for "prune")
```

26 s2c.sh

```
    #!/bin/bash
    #
    #   littlewood -- GPU accelerated Littlewood fractal renderer
    #   Copyright (C) 2012  Claude Heiland-Allen <claude@mathr.co.uk>
 5  #
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    #   it under the terms of the GNU General Public License as published by
    #   the Free Software Foundation, either version 3 of the License, or
    #   (at your option) any later version.
10  #
```

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#   GNU General Public License for more details.
#
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#
echo "/* machine-generated file, do not edit */"
echo "static const char $1[] ="
sed 's|"|\\"|g' |
sed 's|^|"|' |
sed 's|$|\\n"|'
echo ";"
```