fixed-point

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Contents

1 benchmark.cc

```
#include <iostream>

#define CL_TARGET_OPENCL_VERSION 120
#define __CL_ENABLE_EXCEPTIONS
#include <CL/cl.hpp>

#include "fixed-point.c"
const char fixed_point_cl[] = {
#include "fixed-point.c.h"
, 0
};

int main(int argc, char** argv)
{
  if (argc < 10)
  {
    std::fprintf
      ( stderr
      , "usage: %s width height cx cy r maxiters use_fixed use_cl use_bigendian ↙
          ↪ > out.ppm\n"
      , argv[0]
      );
    return 1;
  }
  int subframe = 1;
  int width = atoi(argv[1]);
  int height = atoi(argv[2]);
  double r0 = atof(argv[5]);
  int prec = -log2(2 * r0 / height);
  int b = sizeof(fixed_word_t) * CHAR_BIT;
  int LIMBS = (prec + 8 + b - 1) / b;
  fixed_word_t cx0[1 + LIMBS], cy0[1 + LIMBS];
  fixed_from_string(cx0, 1, LIMBS, argv[3]);
  fixed_from_string(cy0, 1, LIMBS, argv[4]);
  int maxiters = atoi(argv[6]);
```

```
35    bool use_fixed = atoi(argv[7]);
      bool use_cl = atoi(argv[8]);
      bool use_bigendian = atoi(argv[9]);
      if (use_fixed)
      {
40      std::cerr << "fixed format Q1." << LIMBS << std::endl;
      }
      size_t bytes = (size_t) height * width * 3;
      unsigned char* results = new unsigned char[bytes];

45    if (use_cl)
      {
        // OpenCL renderers
        try {
          std::vector<cl::Platform> platforms;
50        cl::Platform::get(&platforms);
          std::vector<cl::Device> platformDevices;
          platforms[0].getDevices(CL_DEVICE_TYPE_GPU, &platformDevices);
          cl::Context context(platformDevices);
          auto contextDevices = context.getInfo<CL_CONTEXT_DEVICES>();
55        auto device = contextDevices[0];
          std::cerr << "Using " << device.getInfo<CL_DEVICE_NAME>() << std::endl;
          cl::Program::Sources source
            ( 1
            , std::make_pair(fixed_point_cl, sizeof(fixed_point_cl) - 1)
60          );
          cl::Program program(context, source);
          try {
            bool device_big_endian = use_bigendian;
#ifdef BIG_ENDIAN
65          bool host_big_endian = true;
#else
            bool host_big_endian = false;
#endif
            char options[100];
70          std::snprintf
              ( options, 100
              , "-D LIMBS=%d%s%s"
              , LIMBS
              , device_big_endian ? " -D BIG_ENDIAN=1" : ""
75            , device_big_endian != host_big_endian ? " -D SWAP_ENDIAN=1" : ""
              );
            program.build(contextDevices, options);
          } catch (cl::Error &e) {
            auto buildlog = program.getBuildInfo<CL_PROGRAM_BUILD_LOG>(device);
80          std::cerr << buildlog << std::endl;
            return 1;
          }
          cl::CommandQueue queue(context, device, CL_QUEUE_PROFILING_ENABLE);
          cl_int err = CL_SUCCESS;
85        cl::Buffer output(context, CL_MEM_WRITE_ONLY, bytes, nullptr, &err);
          cl::NDRange offset(0, 0);
          cl::NDRange global_size(height, width);
          if (use_fixed)
          {
90          cl::Buffer cx0_buffer
              ( context
```

```
            , CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR
            , (1 + LIMBS) * sizeof(fixed_word_t)
            , cx0
            , &err
            );
          cl::Buffer cy0_buffer
            ( context
            , CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR
            , (1 + LIMBS) * sizeof(fixed_word_t)
            , cy0
            , &err
            );
          cl::Kernel mandelbrot(program, "mandelbrot_fixed");
          mandelbrot.setArg(0, output);
          mandelbrot.setArg(1, subframe);
          mandelbrot.setArg(2, height);
          mandelbrot.setArg(3, width);
          mandelbrot.setArg(4, cx0_buffer);
          mandelbrot.setArg(5, cy0_buffer);
          mandelbrot.setArg(6, r0);
          mandelbrot.setArg(7, maxiters);
          queue.enqueueNDRangeKernel(mandelbrot, offset, global_size);
        }
        else
        {
          double cx0_double = fixed_to_double(cx0, 1, LIMBS);
          double cy0_double = fixed_to_double(cy0, 1, LIMBS);
          cl::Kernel mandelbrot(program, "mandelbrot_double");
          mandelbrot.setArg(0, output);
          mandelbrot.setArg(1, subframe);
          mandelbrot.setArg(2, height);
          mandelbrot.setArg(3, width);
          mandelbrot.setArg(4, cx0_double);
          mandelbrot.setArg(5, cy0_double);
          mandelbrot.setArg(6, r0);
          mandelbrot.setArg(7, maxiters);
          queue.enqueueNDRangeKernel(mandelbrot, offset, global_size);
        }
        queue.enqueueBarrierWithWaitList();
        cl::Event readDoneEvent;
        queue.enqueueReadBuffer
          ( output
          , CL_FALSE
          , 0
          , bytes
          , results
          , nullptr
          , &readDoneEvent
          );
        std::vector<cl::Event> readWaitList;
        readWaitList.push_back(readDoneEvent);
        cl::Event::waitForEvents(readWaitList);
      } catch (cl::Error &e) {
        std::cerr << e.what() << ": error code " << e.err() << std::endl;
        return 1;
      }
    }
```

```
  else
  {
    // CPU renderers
    if (use_fixed)
    {
      mandelbrot_fixed
        ( results
        , subframe
        , height
        , width
        , cx0
        , cy0
        , r0
        , maxiters
        , LIMBS
        );
    }
    else
    {
      double cx = fixed_to_double(cx0, 1, LIMBS);
      double cy = fixed_to_double(cy0, 1, LIMBS);
      mandelbrot_double
        ( results
        , subframe
        , height
        , width
        , cx
        , cy
        , r0
        , maxiters
        );
    }
  }
  // output image
  std::fprintf(stdout, "P6\n%d %d\n# cx = ", width, height);
  fixed_dump(stdout, cx0, 1, LIMBS);
  std::fprintf(stdout, "\n# cy = ");
  fixed_dump(stdout, cy0, 1, LIMBS);
  std::fprintf
    ( stdout
    , "\n# r = %.18e\n# maxiters = %d\n# use_fixed = %d\n# use_cl = %d\n255\n"
    , r0
    , maxiters
    , use_fixed
    , use_cl
    );
  std::fwrite(results, bytes, 1, stdout);
  return 0;
}
```

2 fixed-point.c

```
/*
Each number is stored as pointer to limbs, with counts of integer and
fractional parts.

#ifdef BIG_ENDIAN
```

```
    The limbs are stored in big-endian order (each limb
    is stored in native-endian order):

10      -(i-1) ... -2 -1 0 . 1 2 .. f

    The represented value is:

    $$ \sum_{n=0}^{i + f} p\left\[n\right\] b^{i - 1 - n} $$
15
    #else

    The limbs are stored in little-endian order (each limb
    is stored in native-endian order):
20
        f .. 2 1 . 0 -1 -2 ... -(i-1)

    The represented value is:

25  $$ \sum_{n=0}^{i + f} p\left\[n\right\] b^{n - f} $$

    #endif

    where $b = 2^{number of bits in a word}$.
30
    */

    #ifdef __OPENCL_VERSION__

35  // OpenCL

    #pragma OPENCL_EXTENSION cl_khr_fp64 : enable

    #ifndef LIMBS
40  #error LIMBS not defined
    #endif

    // limb types: wordword should have twice the bits of word
    typedef uint fixed_word_t;
45  typedef ulong fixed_wordword_t;

    #define static
    #define inline
    #define assert(x) do{}while(0)
50
    #else

    // C99 / C11 / C++11+VLA / ...

55  #include <assert.h>
    #include <float.h>
    #include <limits.h>
    #include <math.h>
    #include <stdbool.h>
60  #include <stdint.h>
    #include <stdio.h>
    #include <stdlib.h>
```

```
// only used for string->fixed conversion
#include <mpfr.h>

// limb types: wordword should have twice the bits of word
typedef uint32_t fixed_word_t;
typedef uint64_t fixed_wordword_t;

#define __kernel
#define __global
#define __constant const

#endif

static inline
fixed_word_t fixed_msb(const fixed_wordword_t ww)
{
  return ww >> (sizeof(fixed_word_t) * CHAR_BIT);
}

static inline
fixed_word_t fixed_lsb(const fixed_wordword_t ww)
{
  return ww;
}

static inline
fixed_wordword_t fixed_word_mul(fixed_word_t a, fixed_word_t b)
{
  return (fixed_wordword_t) a * (fixed_wordword_t) b;
}

static inline
bool fixed_lt_zero
( const fixed_word_t *a, int ai, int af
)
{
  if (ai == 0 && af == 0)
  {
    return false;
  }
#ifdef BIG_ENDIAN
  int ix = 0;
#else
  int ix = ai + af - 1;
#endif
  return !!(a[ix] & ((fixed_word_t) 1 << (sizeof(fixed_word_t) * CHAR_BIT - 1)));
}

static inline
fixed_word_t fixed_read_be
( const fixed_word_t *a, int ai, int af
, int aw
)
{
  if (ai == 0 && af == 0)
```

```
  {
    return (fixed_word_t) 0;
  }
  if (aw < -(ai - 1))
  {
    // sign extend
    if (fixed_lt_zero(a, ai, af))
    {
      return ~ (fixed_word_t) 0;
    }
    else
    {
      return   (fixed_word_t) 0;
    }
  }
  if (aw >= ai + af)
  {
    // trailing 0
    return (fixed_word_t) 0;
  }
  int ix = (ai - 1) + aw;
  return a[ix];
}

static inline
fixed_word_t fixed_read_le
( const fixed_word_t *a, int ai, int af
, int aw
)
{
  if (ai == 0 && af == 0)
  {
    return (fixed_word_t) 0;
  }
  if (aw < -(ai - 1))
  {
    // sign extend
    if (fixed_lt_zero(a, ai, af))
    {
      return ~ (fixed_word_t) 0;
    }
    else
    {
      return   (fixed_word_t) 0;
    }
  }
  if (aw >= ai + af)
  {
    // trailing 0
    return (fixed_word_t) 0;
  }
  int ix = af - aw;
  return a[ix];
}

static inline
void fixed_write_be
```

```
( fixed_word_t *a, int ai, int af
, int aw
, fixed_word_t w
)
{
  assert(-(ai - 1) <= aw);
  assert(aw <= af);
  int ix = (ai - 1) + aw;
  a[ix] = w;
}

static inline
void fixed_write_le
( fixed_word_t *a, int ai, int af
, int aw
, fixed_word_t w
)
{
  assert(-(ai - 1) <= aw);
  assert(aw <= af);
  int ix = af - aw;
  a[ix] = w;
}

#ifdef BIG_ENDIAN
#define fixed_read  fixed_read_be
#define fixed_write fixed_write_be
#else
#define fixed_read  fixed_read_le
#define fixed_write fixed_write_le
#endif

static inline
fixed_word_t fixed_to_word
( const fixed_word_t *a, int ai, int af
)
{
  return fixed_read(a, ai, af, 0);
}

double fixed_to_double
( const fixed_word_t *a, int ai, int af
)
{
  if (fixed_lt_zero(a, ai, af))
  {
    double o = 0;
    for (int aw = -(ai - 1); aw <= af; ++aw)
    {
      fixed_word_t limb = fixed_read(a, ai, af, aw);
      o += ldexp((double) ~limb, -aw * sizeof(fixed_word_t) * CHAR_BIT);
    }
    return -o;
  }
  else
  {
    double o = 0;
```

```
    for (int aw = -(ai - 1); aw <= af; ++aw)
    {
      fixed_word_t limb = fixed_read(a, ai, af, aw);
      o += ldexp((double) limb, -aw * sizeof(fixed_word_t) * CHAR_BIT);
    }
    return o;
  }
}

void fixed_zero
( fixed_word_t *a, int ai, int af
)
{
  for (int ix = 0; ix < ai + af; ++ix)
  {
    a[ix] = 0;
  }
}

void fixed_copy
(       fixed_word_t *o, int oi, int of
, const fixed_word_t *a, int ai, int af
)
{
  if (o == a && oi == ai && of == af)
  {
    return;
  }
  for (int ow = -(oi - 1); ow <= of; ++ow)
  {
    fixed_word_t w = fixed_read(a, ai, af, ow);
    fixed_write(o, oi, of, ow, w);
  }
  return;
}

void fixed_shift
(       fixed_word_t *o, int oi, int of
, const fixed_word_t *a, int ai, int af
, int b
)
{
  if (b == 0)
  {
    fixed_copy(o, oi, of, a, ai, af);
    return;
  }
  if (b > 0)
  {
    // left to right, to support o == a
    int extract = b % (sizeof(fixed_word_t) * CHAR_BIT);
    int shift = b / (sizeof(fixed_word_t) * CHAR_BIT);
    int ow = -(oi - 1);
    fixed_wordword_t w = 0;
    w <<= sizeof(fixed_word_t) * CHAR_BIT;
    w |= fixed_read(a, ai, af, ow + shift);
    for (; ow <= of; ++ow)
```

```
290       {
            w <<= sizeof(fixed_word_t) * CHAR_BIT;
            w |= fixed_read(a, ai, af, ow + (shift + 1));
            fixed_write(o, oi, of, ow, fixed_msb(w << extract));
          }
295       return;
        }
        if (b < 0)
        {
          // right to left, to support o == a
300       b = -b;
          int extract = b % (sizeof(fixed_word_t) * CHAR_BIT);
          int shift = b / (sizeof(fixed_word_t) * CHAR_BIT);
          int ow = of;
          fixed_wordword_t w = 0;
305       w >>= sizeof(fixed_word_t) * CHAR_BIT;
          w |= (fixed_wordword_t) fixed_read(a, ai, af, ow - shift)
              << (sizeof(fixed_word_t) * CHAR_BIT);
          for (; ow >= -(oi - 1); --ow)
          {
310         w >>= sizeof(fixed_word_t) * CHAR_BIT;
            w |= (fixed_wordword_t) fixed_read(a, ai, af, ow - (shift + 1))
                << (sizeof(fixed_word_t) * CHAR_BIT);
            fixed_write(o, oi, of, ow, fixed_lsb(w >> extract));
          }
315       return;
        }
      }

      fixed_word_t fixed_neg
320   (       fixed_word_t *o, int oi, int of
      , const fixed_word_t *a, int ai, int af
      )
      {
        fixed_word_t carry = 1;
325     for (int ow = of; ow >= -(oi - 1); --ow)
        {
          fixed_word_t in_a = fixed_read(a, ai, af, ow);
          fixed_word_t not_a = ~in_a;
          fixed_word_t a_result = not_a + carry;
330       carry = a_result < not_a ? 1 : 0;
          fixed_write(o, oi, of, ow, a_result);
        }
        return carry;
      }
335
      void fixed_from_word
      ( fixed_word_t *a, int ai, int af
      , fixed_word_t x
      )
340   {
        fixed_zero(a, ai, af);
        fixed_write(a, ai, af, 0, x);
      }

345   void fixed_from_double
      ( fixed_word_t *a, int ai, int af
```

```
    , double x
    )
    {
350   // FIXME may be inaccurate if 2 > af
      assert(FLT_RADIX == 2);
      if (x == 0)
      {
        fixed_zero(a, ai, af);
355     return;
      }
      bool negate = x < 0;
      if (negate) x = -x;
      int e = 0;
360   x = frexp(x, &e);
      // [0.5 .. 1), original value is x * 2^e
      for (int aw = -(ai - 1); aw <= 0; ++ aw)
      {
        fixed_write(a, ai, af, aw, 0);
365   }
      for (int aw = 1; aw <= af; ++aw)
      {
        x = ldexp(x, sizeof(fixed_word_t) * CHAR_BIT);
        fixed_word_t w = floor(x);
370     x -= (double) w;
        fixed_write(a, ai, af, aw, w);
        // also writes trailing 0s
      }
      fixed_shift(a, ai, af, a, ai, af, e);
375   if (negate)
      {
        fixed_neg(a, ai, af, a, ai, af);
      }
      return;
380 }

    fixed_word_t fixed_add
    (       fixed_word_t *o, int oi, int of
    , const fixed_word_t *a, int ai, int af
385 , const fixed_word_t *b, int bi, int bf
    )
    {
      fixed_word_t carry = 0;
      for (int ow = of; ow >= -(oi - 1); --ow)
390   {
        fixed_word_t in_a = fixed_read(a, ai, af, ow);
        fixed_word_t in_b = fixed_read(b, bi, bf, ow);
        fixed_word_t a_result = in_a + carry;
        fixed_word_t a_carry = a_result < in_a ? 1 : 0;
395     fixed_word_t b_result = in_b + a_result;
        fixed_word_t b_carry = b_result < in_b ? 1 : 0;
        carry = a_carry + b_carry;
        fixed_write(o, oi, of, ow, b_result);
      }
400   return carry;
    }

    fixed_word_t fixed_sub
```

```
(       fixed_word_t *o, int oi, int of
, const fixed_word_t *a, int ai, int af
, const fixed_word_t *b, int bi, int bf
)
{
  fixed_word_t borrow = 0;
  for (int ow = of; ow >= -(oi - 1); --ow)
  {
    fixed_word_t in_a = fixed_read(a, ai, af, ow);
    fixed_word_t in_b = fixed_read(b, bi, bf, ow);
    fixed_word_t a_result = in_a - borrow;
    fixed_word_t a_borrow = borrow > in_a ? 1 : 0;
    fixed_word_t b_result = a_result - in_b;
    fixed_word_t b_borrow = in_b > a_result ? 1 : 0;
    borrow = a_borrow + b_borrow;
    fixed_write(o, oi, of, ow, b_result);
  }
  return borrow;
}

fixed_word_t fixed_mul
(       fixed_word_t *o, int oi, int of
, const fixed_word_t *a, int ai, int af
, const fixed_word_t *b, int bi, int bf
)
{
  fixed_wordword_t accum = 0;
  fixed_wordword_t carry = 0;
  for (int ow = of; ow >= -(oi - 1); --ow)
  {
    accum = fixed_lsb(carry);
    carry = fixed_msb(carry);
    if (ow == of)
    {
      // sum fixed_msb over aw + bw = ow + 1, aw <= af, bw <= bf
      for (int aw = ow + 1 - bf; aw <= af; ++aw)
      {
        int bw = ow + 1 - aw;
        fixed_word_t in_a = fixed_read(a, ai, af, aw);
        fixed_word_t in_b = fixed_read(b, bi, bf, bw);
        fixed_wordword_t ab = fixed_word_mul(in_a, in_b);
        accum += fixed_msb(ab);
      }
    }
    // sum fixed_lsb over aw + bw = ow, aw <= af, bw <= bf
    for (int aw = ow - bf; aw <= af; ++aw)
    {
      int bw = ow - aw;
      fixed_word_t in_a = fixed_read(a, ai, af, aw);
      fixed_word_t in_b = fixed_read(b, bi, bf, bw);
      fixed_wordword_t ab = fixed_word_mul(in_a, in_b);
      accum += fixed_lsb(ab);
      carry += fixed_msb(ab);
    }
    fixed_write(o, oi, of, ow, fixed_lsb(accum));
    carry += fixed_msb(accum);
  }
```

```
  return fixed_lsb(carry);
}

fixed_word_t fixed_sqr
(       fixed_word_t *o, int oi, int of
, const fixed_word_t *a, int ai, int af
)
{
  fixed_wordword_t accum = 0;
  fixed_wordword_t carry = 0;
  for (int ow = of; ow >= -(oi - 1); --ow)
  {
    accum = fixed_lsb(carry);
    carry = fixed_msb(carry);
    if (ow == of)
    {
      // sum fixed_msb over aw + bw = ow + 1, aw <= af, bw <= bf, exploiting symmetry
      for (int aw = ow + 1 - af; aw <= af; ++aw)
      {
        int bw = ow + 1 - aw;
        if (aw <= bw)
        {
          fixed_word_t in_a = fixed_read(a, ai, af, aw);
          fixed_word_t in_b = aw == bw ? in_a : fixed_read(a, ai, af, bw);
          fixed_wordword_t ab = fixed_word_mul(in_a, in_b);
          if (aw != bw)
          {
            accum += (fixed_wordword_t) fixed_msb(ab) << 1;
          }
          else
          {
            accum += fixed_msb(ab);
          }
        }
      }
    }
    // sum fixed_lsb over aw + bw = ow, aw <= af, bw <= bf, exploiting symmetry
    for (int aw = ow - af; aw <= af; ++aw)
    {
      int bw = ow - aw;
      if (aw <= bw)
      {
        fixed_word_t in_a = fixed_read(a, ai, af, aw);
        fixed_word_t in_b = aw == bw ? in_a : fixed_read(a, ai, af, bw);
        fixed_wordword_t ab = fixed_word_mul(in_a, in_b);
        if (aw != bw)
        {
          accum += (fixed_wordword_t) fixed_lsb(ab) << 1;
          carry += (fixed_wordword_t) fixed_msb(ab) << 1;
        }
        else
        {
          accum += fixed_lsb(ab);
          carry += fixed_msb(ab);
        }
      }
```

```
    }
    fixed_write(o, oi, of, ow, fixed_lsb(accum));
    carry += fixed_msb(accum);
  }
  return fixed_lsb(carry);
}

static inline
double double_sqr(double x)
{
  return x * x;
}

double mandelbrot_double_core(double cx, double cy, int maxiters)
{
  double zx = 0;
  double zy = 0;
  for (int n = 0; n < maxiters; ++n)
  {
    double zx2 = double_sqr(zx);
    double zy2 = double_sqr(zy);
    double z2 = zx2 + zy2;
    if (z2 >= 256)
    {
      return n + 1 - log2(0.5 * log(z2));
    }
    double zxy = zx * zy;
    zx = zx2 - zy2 + cx;
    zy = 2 * zxy + cy;
  }
  return 1.0 / 0.0; // infinity for interior
}

/*
local memory usage in bytes:

    ((i + f) * 5 + 3) * sizeof(word)

*/
double mandelbrot_fixed_core
( const fixed_word_t *cx
, const fixed_word_t *cy
, int maxiters
#ifdef __OPENCL_VERSION__
// no VLA, use global #define
#else
, int LIMBS
#endif
)
{
#define i 1
#define f LIMBS
#define w (i + f)
  fixed_word_t zx[w], zy[w], zx2[w], zy2[w], zxy[w], z2[1+2];
  fixed_zero(zx, i, f);
  fixed_zero(zy, i, f);
  for (int n = 0; n < maxiters; ++n)
```

```
    {
      fixed_sqr(zx2, i, f, zx, i, f);
      fixed_sqr(zy2, i, f, zy, i, f);
      fixed_add(z2, 1, 2, zx2, i, f, zy2, i, f);
      if (fixed_to_word(z2, 1, 2) >= 256)
      {
        double d = fixed_to_double(z2, 1, 2);
        return n + 1 - log2(0.5 * log(d));
      }
      fixed_mul(zxy, i, f, zx, i, f, zy, i, f);
      fixed_sub(zx, i, f, zx2, i, f, zy2, i, f);
      fixed_add(zx, i, f, zx, i, f, cx, i, f);
      fixed_shift(zy, i, f, zxy, i, f, 1);
      fixed_add(zy, i, f, zy, i, f, cy, i, f);
    }
    return 1.0 / 0.0; // infinity for interior
#undef i
#undef f
#undef w
}

fixed_word_t hash_burtle_9(fixed_word_t a)
{
  // FIXME assumes 32bit word
  a = (a+0x7ed55d16u) + (a<<12u);
  a = (a^0xc761c23cu) ^ (a>>19u);
  a = (a+0x165667b1u) + (a<<5u);
  a = (a+0xd3a2646cu) ^ (a<<9u);
  a = (a+0xfd7046c5u) + (a<<3u);
  a = (a^0xb55a4f09u) ^ (a>>16u);
  return a;
}

double uniform01(int seed)
{
  fixed_word_t r = hash_burtle_9(seed);
  return (double)(r) / ((double)(fixed_word_t)(-1) + 1);
}

__kernel
void mandelbrot_double
( __global unsigned char* output
, int subframe
, int height
, int width
, double cx0
, double cy0
, double r0
, int maxiters
)
{
#ifdef __OPENCL_VERSION__
 int y = get_global_id(0);
 int x = get_global_id(1);
#else
 #pragma omp parallel for
 for (int y = 0; y < height; ++y)
```

```
  for (int x = 0; x < width; ++x)
#endif
  {
    int k = (y * width + x) * 3;
    int seed = subframe * width * height + y * width + x;
    double dx = 2 * r0 * ((x + uniform01(2 * seed + 0)) / width  - 0.5) * width / ↙
        ↳ height;
    double dy = 2 * r0 * ((height - (y + uniform01(2 * seed + 1))) / height - 0.5)↙
        ↳ ;
    double mu = mandelbrot_double_core(cx0 + dx, cy0 + dy, maxiters);
    if (mu == -1.0 / 0.0)
    {
      output[k + 0] = 0;
      output[k + 1] = 0;
      output[k + 2] = 0;
    }
    else
    {
      output[k + 0] = 255 * (0.5 - 0.5 * cos(mu / 1  ));
      output[k + 1] = 255 * (0.5 - 0.5 * cos(mu / 10 ));
      output[k + 2] = 255 * (0.5 - 0.5 * cos(mu / 100));
    }
  }
}

__kernel
void mandelbrot_fixed
( __global unsigned char* output
, int subframe
, int height
, int width
, __constant fixed_word_t *cx0
, __constant fixed_word_t *cy0
, double r0
, int maxiters
#ifdef __OPENCL_VERSION__
// no VLA, use global #define
#else
, int LIMBS
#endif
)
{
#ifdef __OPENCL_VERSION__
  int y = get_global_id(0);
  int x = get_global_id(1);
#else
 #pragma omp parallel for
  for (int y = 0; y < height; ++y)
  for (int x = 0; x < width; ++x)
#endif
  {
    int k = (y * width + x) * 3;
    int seed = subframe * width * height + y * width + x;
    double dx = 2 * r0 * ((x + uniform01(2 * seed + 0)) / width  - 0.5) * width / ↙
        ↳ height;
    double dy = 2 * r0 * ((height - (y + uniform01(2 * seed + 1))) / height - 0.5)↙
        ↳ ;
```

```
    fixed_word_t cx[1+LIMBS], cy[1+LIMBS];
    fixed_from_double(cx, 1, LIMBS, dx);
    fixed_from_double(cy, 1, LIMBS, dy);
    {
      fixed_word_t t[1+LIMBS];
      for (int i = 0; i <= LIMBS; ++i)
      {
#ifdef SWAP_ENDIAN
        t[i] = cx0[LIMBS - i];
#else
        t[i] = cx0[i];
#endif
      }
      fixed_add(cx, 1, LIMBS, cx, 1, LIMBS, t, 1, LIMBS);
      for (int i = 0; i <= LIMBS; ++i)
      {
#ifdef SWAP_ENDIAN
        t[i] = cy0[LIMBS - i];
#else
        t[i] = cy0[i];
#endif
      }
      fixed_add(cy, 1, LIMBS, cy, 1, LIMBS, t, 1, LIMBS);
    }
    double mu = mandelbrot_fixed_core
      ( cx
      , cy
      , maxiters
#ifdef __OPENCL_VERSION__
      // no VLA, use global #define
#else
      , LIMBS
#endif
      );
    if (mu == -1.0 / 0.0)
    {
      output[k + 0] = 0;
      output[k + 1] = 0;
      output[k + 2] = 0;
    }
    else
    {
      output[k + 0] = 255 * (0.5 - 0.5 * cos(mu / 1  ));
      output[k + 1] = 255 * (0.5 - 0.5 * cos(mu / 10 ));
      output[k + 2] = 255 * (0.5 - 0.5 * cos(mu / 100));
    }
  }
}

#ifndef __OPENCL_VERSION__

void fixed_dump
( FILE *f
, const fixed_word_t *a, int ai, int af
)
{
  for (int aw = -(ai - 1); aw <= 0; ++aw)
```

```
    {
      fprintf(f, "%08x", fixed_read(a, ai, af, aw));
      if (aw < 0) fputc(' ', f);
    }
    fputc('.', f);
    for (int aw = 1; aw <= af; ++aw)
    {
      fprintf(f, "%08x", fixed_read(a, ai, af, aw));
      if (aw < af) fputc(' ', f);
    }
}

void fixed_from_mpfr
( fixed_word_t *a, int ai, int af
, const mpfr_t x
)
{
  fixed_word_t b[ai + af];
  mpfr_t y;
  mpfr_init2(y, mpfr_get_prec(x));
  mpfr_set(y, x, MPFR_RNDN);
  fixed_zero(a, ai, af);
  double limb;
  do
  {
    limb = mpfr_get_d(y, MPFR_RNDN);
    mpfr_sub_d(y, y, limb, MPFR_RNDN);
    fixed_from_double(b, ai, af, limb);
    fixed_add(a, ai, af, a, ai, af, b, ai, af);
  } while (limb != 0);
  mpfr_clear(y);
}

void fixed_from_string
( fixed_word_t *a, int ai, int af
, const char *x
)
{
  mpfr_t y;
  mpfr_init2(y, (ai + af + 1) * sizeof(fixed_word_t) * CHAR_BIT);
  mpfr_set_str(y, x, 10, MPFR_RNDN);
  fixed_from_mpfr(a, ai, af, y);
  mpfr_clear(y);
}

#endif
```

3 .gitignore

```
benchmark-be
benchmark-le
fixed-point.c.h
*.ppm
*.png
```

4 LICENSE.md

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Version 3, 19 November 2007

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```

5 Makefile

```
all: benchmark-be benchmark-le

benchmark-be: benchmark.cc fixed-point.c fixed-point.c.h
	g++ -std=c++11 -pedantic -Wall -Wextra -Wno-vla -O3 -march=native -↙
	    ↳ fopenmp -o $@ benchmark.cc -lOpenCL -lmpfr -lm -DBIG_ENDIAN=1

benchmark-le: benchmark.cc fixed-point.c fixed-point.c.h
	g++ -std=c++11 -pedantic -Wall -Wextra -Wno-vla -O3 -march=native -↙
	    ↳ fopenmp -o $@ benchmark.cc -lOpenCL -lmpfr -lm -UBIG_ENDIAN

%.c.h: %.c
	xxd -i < $< > $@
```

6 README.md

```
# fixed-point

A simple fixed-point implementation in C99 / C11 / C++11+VLA / OpenCL,
with a Mandelbrot set example.

## benchmark
```

```
This location can go to 1e-90 or so, need to increase iterations to
200000 for that.

    make
    export re↙
        ↳ =0.3008061094509125010127446384643058055750411964658177250083952891549962162150804769
        ↳
    export im↙
        ↳ =0.0201493838545236659545079551774242325148417581270203645159757400083017169679011465
        ↳
    export zoom=1e-15
    export iterations=1000
    for host_endian in le be ; do
    for use_fixed in 0 1 ; do
    for use_cl in 0 1 ; do
    for device_bigendian in $(seq 0 $use_cl) ; do
      time ./benchmark-$host_endian 1920 1080 "$re" "$im" "$zoom" "$iterations" ↙
          ↳ "$use_fixed" "$use_cl" "$use_bigendian" > "${host_endian}-${↙
          ↳ use_fixed}-${use_cl}-${device_bigendian}.ppm"
    done ; done ; done ; done

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## references

- OpenCL C++ driver code example simplified from `mandelbrot_cl.cpp` from
<http://distrustsimplicity.net/articles/mandelbrot-speed-comparison/>
```