ImgLib2

Generische Bildverarbeitung in Java

Tobias Pietzsch, Stephan Preibisch & Stephan Saalfeld

Max Planck Institute of Molecular Cell Biology and Genetics, Dresden

Java User Group Saxony, 8. November 2012 http://imglib2.net

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Motivation

- Image data sets in the life sciences:
  - *n*-dimensional,
  - multi-modal,
  - excessive size
- Algorithmic concepts from image processing are applicable, but Algorithm implementations are often not re-usable:
  - implemented for fixed dimensionality (often 2d),
  - specific data type,
  - limited image size.
- Goal: code that is independent of image dimensionality, data type, and data storage strategy.

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  - specific data type,
  - limited image size.
- Goal: code that is independent of image dimensionality, data type, and data storage strategy.

Find Maximum: ImageJ 2D

```java
/** ImageProcessor efficient two-dimensional */
public float findMax2(final ImageProcessor ip, final int[] location) {
  float max = ip.getf(0);
  int maxIndex = 0;
  final int n = ip.getPixelCount();
  for (int i = 1; i < n; ++i) {
    final float pixel = ip.getf(i);
    if (pixel > max) {
      max = pixel;
      maxIndex = i;
    }
  }
  location[1] = maxIndex / ip.getWidth();
  location[0] = maxIndex - location[1] * ip.getWidth();
  return max;
}
```

Find Maximum: ImageJ 3D

```java
/** ImageProcessor efficient three-dimensional */
public float findMax3(final ImagePlus imp, final int[] location) {
  final int n = imp.getWidth() * imp.getHeight();
  float max = (float) imp.getStack().getVoxel(0, 0, 0);
  int maxIndex = 0, maxZ = 0;
  for (int z = 0; z < imp.getNSlices(); ++z) {
    final ImageProcessor ip = imp.getStack().getProcessor(z + 1);
    for (int i = 0; i < n; ++i) {
      final float pixel = ip.getf(i);
      if (pixel > max) {
        max = pixel;
        maxIndex = i;
        maxZ = z;
      }
    }
  }
  location[2] = maxZ;
  location[1] = maxIndex / imp.getWidth();
  location[0] = maxIndex - location[1] * imp.getWidth();
  return max;
}
```

Find Maximum: ImageJ 4D

```java
/** ImageProcessor efficient four-dimensional */
public float findMax4(final ImagePlus imp, final int[] location) {
  final int n = imp.getWidth() * imp.getHeight();
  float max = imp.getStack().getProcessor(1).getf(0);
  int maxIndex = 0, maxZ = 0, maxT = 0;
  for (int t = 0; t < imp.getNFrames(); ++t) {
    for (int z = 0; z < imp.getNSlices(); ++z) {
      final ImageProcessor ip =
          imp.getStack().getProcessor(imp.getStackIndex(1, z + 1, t + 1));
      for (int i = 0; i < n; ++i) {
        final float pixel = ip.getf(i);
        if (pixel > max) {
          max = pixel;
          maxIndex = i;
          maxZ = z;
          maxT = t;
        }
      }
    }
  }
  location[3] = maxT;
  location[2] = maxZ;
  location[1] = maxIndex / imp.getWidth();
  location[0] = maxIndex - location[1] * imp.getWidth();
  return max;
}
```

Find Maximum: ImgLib2

```java
/** ImgLib2 generic */
public <T extends Comparable<T>> Cursor<T> findMax(
    final IterableInterval<T> img) {
  final Cursor<T> cursor = img.cursor();
  cursor.fwd();
  Cursor<T> max = cursor.copyCursor();
  while (cursor.hasNext())
    if (cursor.next().compareTo(max.get()) > 0) {
      max = cursor.copyCursor();
    }
  return max;
}
```

Find Maximum: ImgLib2 real coordinates

```java
/** ImgLib2 generic real coordinates */
public <T extends Comparable<T>> RealCursor<T> findMax(
    final IterableRealInterval<T> img) {
  final RealCursor<T> cursor = img.cursor();
  cursor.fwd();
  RealCursor<T> max = cursor.copyCursor();
  while (cursor.hasNext())
    if (cursor.next().compareTo(max.get()) > 0) {
      max = cursor.copyCursor();
    }
  return max;
}
```

ImgLib2

Library for *n*-dimensional data representation and manipulation.

Goals:

- Dimensionality-, type-, and storage-independent algorithms.
- Decouple algorithm development and data management.
- Extensibility (adding algorithms, pixel types, storage strategies).
- Adaptability (to existing data structures).

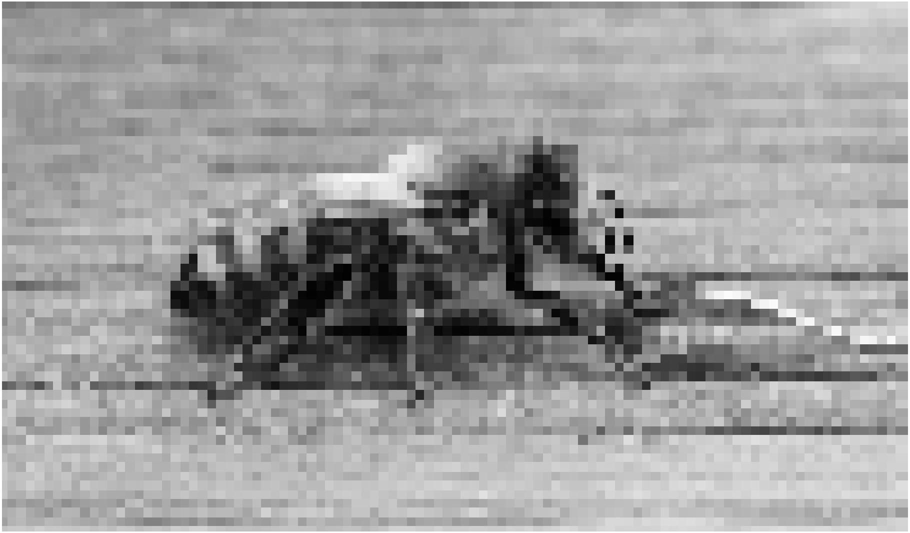
ImgLib2

- ImageJ2
- Fiji
- Knime Image Processing (KNIP)
- Omero

Outline

1. What is an Image in ImgLib2?
2. Architecture
   - Type Hierarchy - Pixels
   - Accessors - Image Access Patterns
   - Accessibles - Images
   - Virtualized Pixel Access
3. Performance

What is an Image in ImgLib2?



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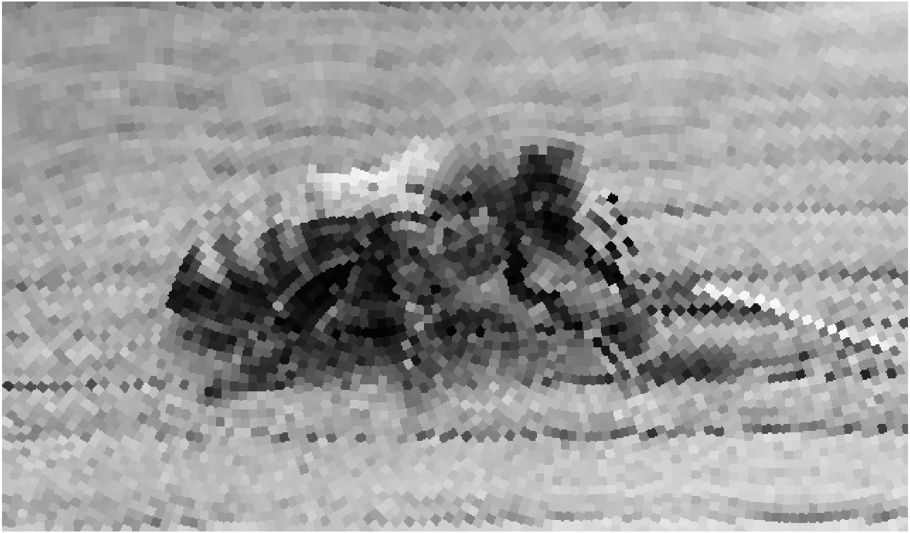

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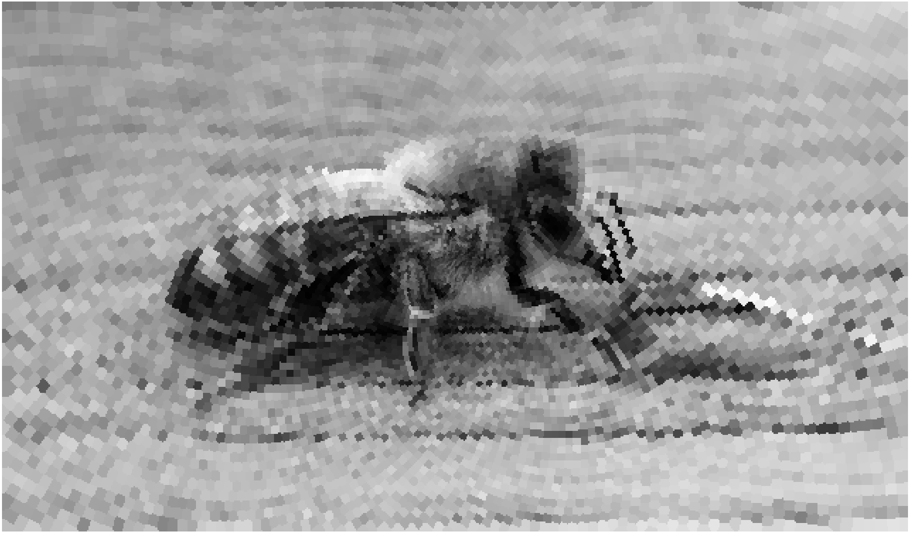

What is an Image in ImgLib2?

$$f : \Omega \to \mathbb{T} \quad \text{with} \quad \Omega \subset \mathbb{R}^n$$

- Arbitrary co-domain $\mathbb{T}$.
- Bounded or un-bounded domain Ω.
- Integer or real coordinates.
- Discrete (grid or sparsely sampled) or continuous domain.

Examples:

- 1D, 2D, . . . , *n*D pixel image.
- interpolated pixel image.
- (interpolated) sparse *n*D sample set.
- virtualized view into another image (transformed, sliced, . . .).
- procedurally generated image.

. . .

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- procedurally generated image.

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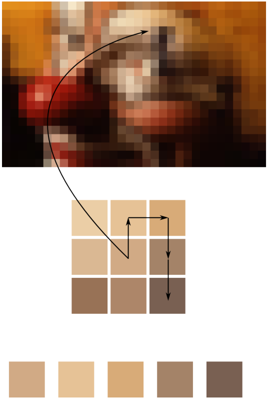
Architecture

Main abstractions:

- Accessible ("Image")
  - Provides Accessors.
  - May provide bounds.
- Accessor
  - Is moved across the image.
  - Provides access to Types.
- Type ("Pixel value")
  - Represents sample value $\in \mathbb{T}$.
  - Operations on $\mathbb{T}$.



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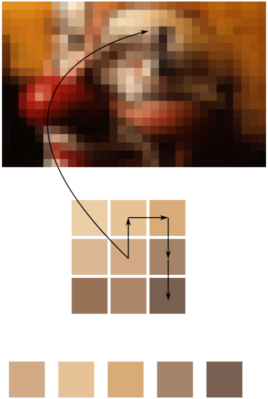
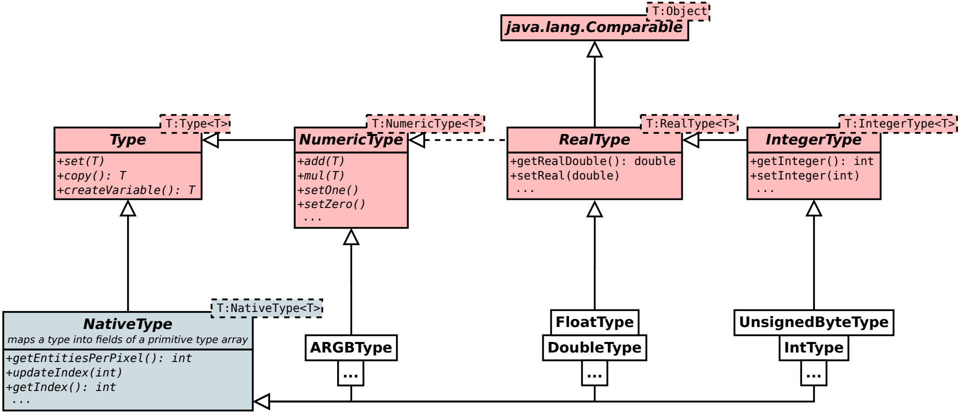


Types (Pixels)



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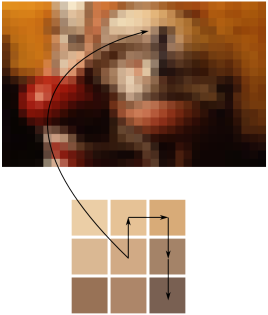


Access Patterns - Random Access

Random Access:

- Retrieve pixels at specific coordinates.

```
RandomAccess<T> access = image.randomAccess();
access.setPosition(new long[] {100, 100});
access.fwd(1);
...
T value = access.get();
...
```

Access Patterns - Random Access

Random Access:

- Retrieve pixels at specific coordinates.

```
RealRandomAccess<T> access = image.realRandomAccess();
access.setPosition(new double[] {42.1, 0.783});
access.fwd(1);
...
T value = access.get();
...
```

Access Patterns - Iteration

Iteration:

- Visit every pixel once.
- Iteration order is irrelevant.

```
RandomAccess<T> access = image.randomAccess();
for( long x = minX; x <= maxX; ++x ) {
  for( long y = minY; y <= maxY; ++y ) {
    for( long z = minZ; z <= maxZ; ++z ) {
      for( long t = minT; t <= maxT; ++t ) {
        for( long c = minC; c <= maxC; ++c ) {
          access.setPosition(new long[] {x,y,z,t,c});
          T value = access.get();
          ...
        }
      }
    }
  }
}
```

Access Patterns - Iteration

Iteration:

- Visit every pixel once.
- Iteration order is irrelevant.

```
Cursor<T> cursor = image.cursor();
while (cursor.hasNext()) {
  T value = cursor.next();
  ...
}
```

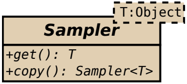
Access Patterns - Iteration

Iteration:

- Visit every pixel once.
- Iteration order is irrelevant.

```
for (T value : image ) {
   ...
}
```

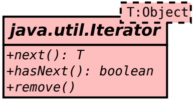
Accessors



T:Object

Sampler

+get(): T
+copy(): Sampler<T>

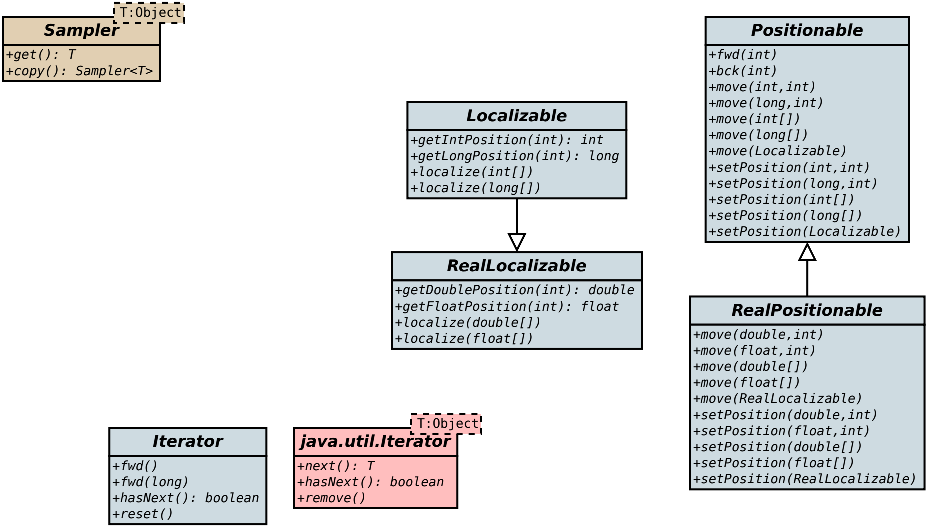


T:Object

java.util.Iterator

+next(): T
+hasNext(): boolean
+remove()

Accessors



Sampler T:Object

+get(): T

+copy(): Sampler<T>

Localizable

+getIntPosition(int): int

+getLongPosition(int): long

+localize(int[])

+localize(long[])

RealLocalizable

+getDoublePosition(int): double

+getFloatPosition(int): float

+localize(double[])

+localize(float[])

Positionable

+fwd(int)

+bck(int)

+move(int,int)

+move(long,int)

+move(int[])

+move(long[])

+move(Localizable)

+setPosition(int,int)

+setPosition(long,int)

+setPosition(int[])

+setPosition(long[])

+setPosition(Localizable)

RealPositionable

+move(double,int)

+move(float,int)

+move(double[])

+move(float[])

+move(RealLocalizable)

+setPosition(double,int)

+setPosition(float,int)

+setPosition(double[])

+setPosition(float[])

+setPosition(RealLocalizable)

Iterator

+fwd()

+fwd(long)

+hasNext(): boolean

+reset()

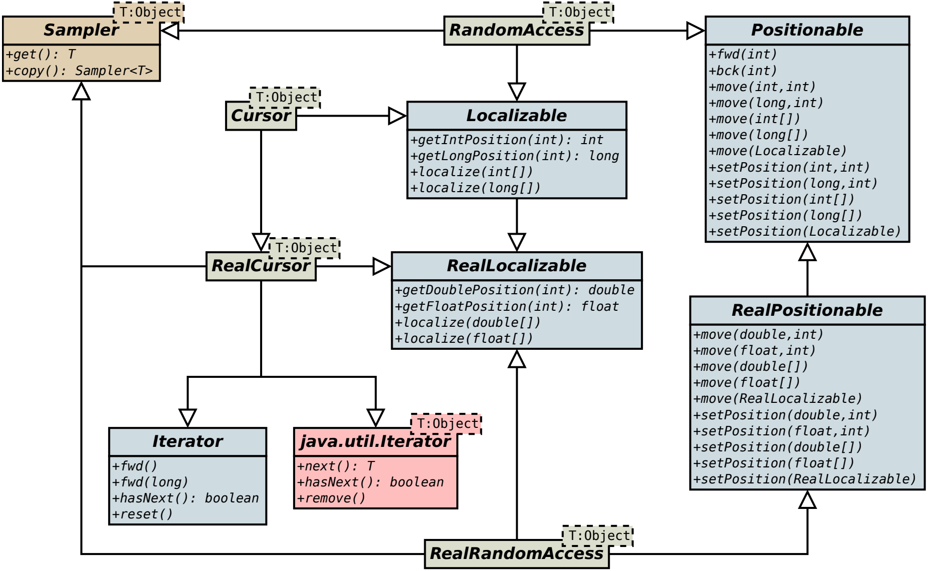
java.util.Iterator T:Object

+next(): T

+hasNext(): boolean

+remove()

Accessors


T:Object
Sampler
+get(): T
+copy(): Sampler<T>
T:Object
RandomAccess
Positionable
+fwd(int)
+bck(int)
+move(int,int)
+move(long,int)
+move(int[])
+move(long[])
+move(Localizable)
+setPosition(int,int)
+setPosition(long,int)
+setPosition(int[])
+setPosition(long[])
+setPosition(Localizable)
T:Object
Cursor
Localizable
+getIntPosition(int): int
+getLongPosition(int): long
+localize(int[])
+localize(long[])
T:Object
RealCursor
RealLocalizable
+getDoublePosition(int): double
+getFloatPosition(int): float
+localize(double[])
+localize(float[])
RealPositionable
+move(double,int)
+move(float,int)
+move(double[])
+move(float[])
+move(RealLocalizable)
+setPosition(double,int)
+setPosition(float,int)
+setPosition(double[])
+setPosition(float[])
+setPosition(RealLocalizable)
Iterator
+fwd()
+fwd(long)
+hasNext(): boolean
+reset()
T:Object
java.util.Iterator
+next(): T
+hasNext(): boolean
+remove()
T:Object
RealRandomAccess

Architecture

Main abstractions:

- Accessible (“Image”)
  - Provides Accessors.
  - May provide bounds.
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  - Provides access to Types.
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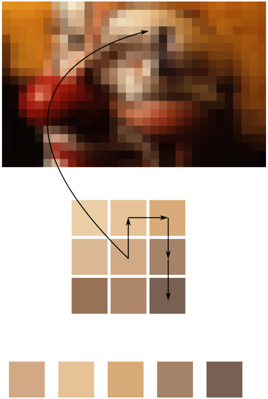
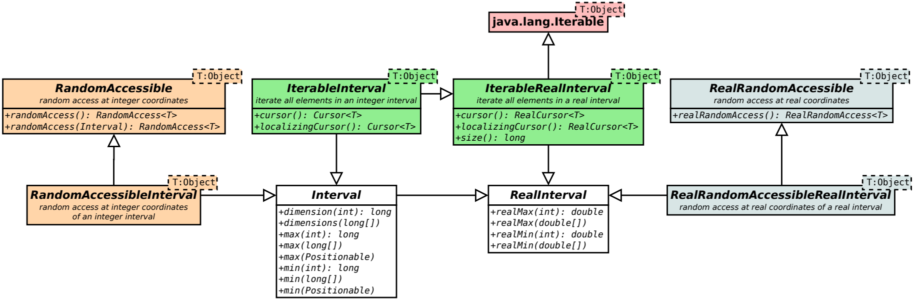


What is an Image in ImgLib2?

$$f : \Omega \rightarrow \mathbb{T} \quad \text{with} \quad \Omega \subseteq \mathbb{R}^n$$

$\Omega = \mathbb{R}^n$	RealRandomAccessible<T>
$\Omega = [\vec{min}, \vec{max}]; \vec{min}, \vec{max} \in \mathbb{R}^n$	RealRandomAccessibleRealInterval<T>
$\Omega = \{\vec{x}_1 \ldots \vec{x}_n\}; \vec{x}_i \in \mathbb{R}^n$	IterableRealInterval<T>
$\Omega = \mathbb{Z}^n$	RandomAccessible<T>
$\Omega = [\vec{min}, \vec{max}]; \vec{min}, \vec{max} \in \mathbb{Z}^n$	RandomAccessibleInterval<T>
$\Omega = \{\vec{x}_1 \ldots \vec{x}_n\}; \vec{x}_i \in \mathbb{Z}^n$	IterableInterval<T>

Accessibles (Collections)



T:Object
java.lang.Iterable

T:Object
RandomAccessible
random access at integer coordinates
+randomAccess(): RandomAccess<T>
+randomAccess(Interval): RandomAccess<T>

T:Object
IterableInterval
iterate all elements in an integer interval
+cursor(): Cursor<T>
+localizingCursor(): Cursor<T>

T:Object
IterableRealInterval
iterate all elements in a real interval
+cursor(): RealCursor<T>
+localizingCursor(): RealCursor<T>
+size(): long

T:Object
RealRandomAccessible
random access at real coordinates
+realRandomAccess(): RealRandomAccess<T>

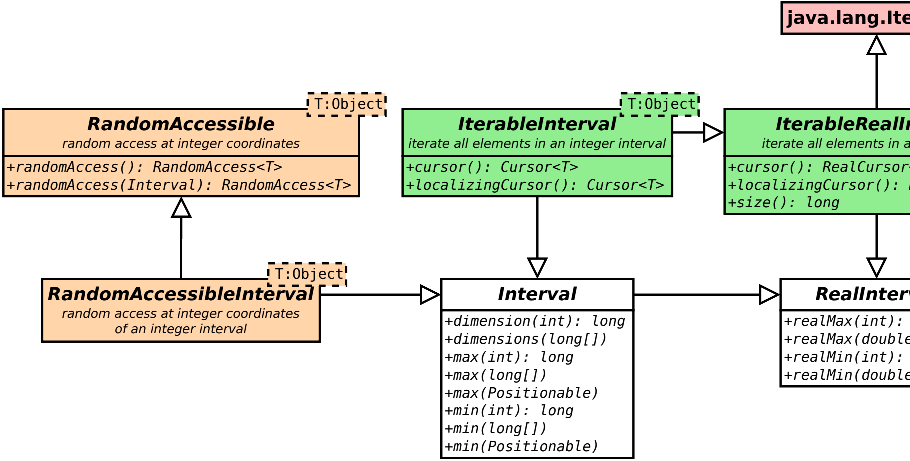
T:Object
RandomAccessibleInterval
random access at integer coordinates
of an integer interval

Interval
+dimension(int): long
+dimensions(long[])
+max(int): long
+max(long[])
+max(Positionable)
+min(int): long
+min(long[])
+min(Positionable)

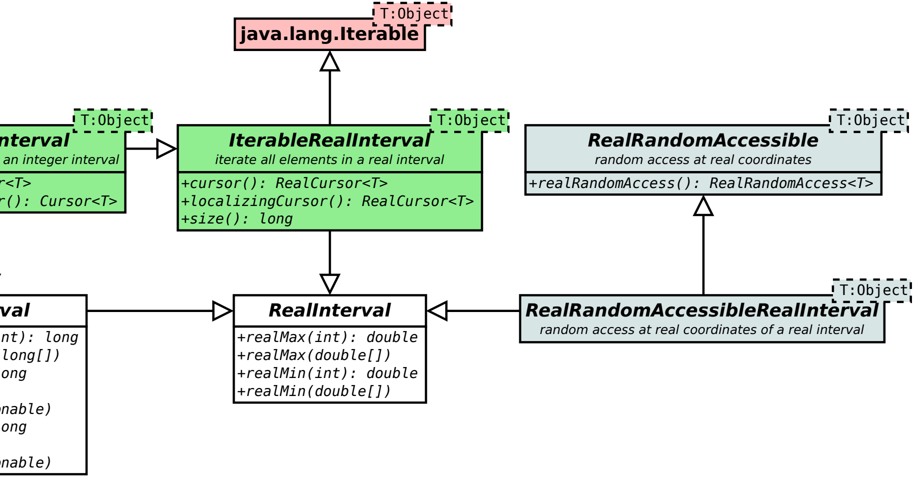
RealInterval
+realMax(int): double
+realMax(double[])
+realMin(int): double
+realMin(double[])

T:Object
RealRandomAccessibleRealInterval
random access at real coordinates of a real interval

Accessibles (Collections)



Accessibles (Collections)



T:Object
java.lang.Iterable

T:Object
nterval
an integer interval
r<T>
r(): Cursor<T>

T:Object
IterableRealInterval
iterate all elements in a real interval
+cursor(): RealCursor<T>
+localizingCursor(): RealCursor<T>
+size(): long

T:Object
RealRandomAccessible
random access at real coordinates
+realRandomAccess(): RealRandomAccess<T>

val
nt): long
long[])
ong
nable)
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nable)

RealInterval
+realMax(int): double
+realMax(double[])
+realMin(int): double
+realMin(double[])

T:Object
RealRandomAccessibleRealInterval
random access at real coordinates of a real interval

Accessibles - Neighborhoods

Accessibles are not restricted to contain Types.

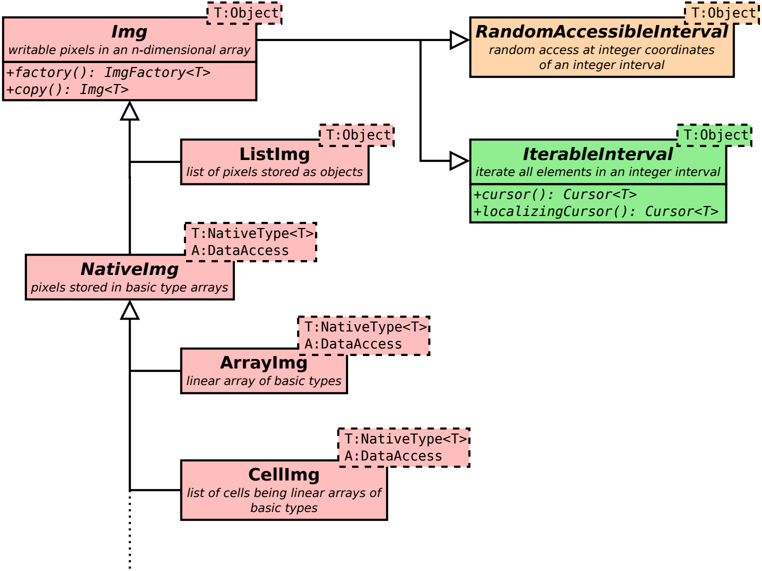
```
IterableInterval<T> image;
for (T value : image ) {
   ...
}
```

Accessibles - Neighborhoods

Accessibles are not restricted to contain Types.

```
IterableInterval<Neighborhood<T>> neighborhoods;
for (Neighborhood<T> neighborhood : neighborhoods) {
  for (T value : neighborhood ) {
    ...
  }
}
```

Pixel Images



T:Object

Img

writable pixels in an n-dimensional array

+factory(): ImgFactory<T>
+copy(): Img<T>

T:Object

ListImg

list of pixels stored as objects

T:NativeType<T>
A:DataAccess

NativeImg

pixels stored in basic type arrays

T:NativeType<T>
A:DataAccess

ArrayImg

linear array of basic types

T:NativeType<T>
A:DataAccess

CellImg

list of cells being linear arrays of basic types

T:Object

RandomAccessibleInterval

random access at integer coordinates of an integer interval

T:Object

IterableInterval

iterate all elements in an integer interval

+cursor(): Cursor<T>
+localizingCursor(): Cursor<T>

Virtualized Sample Access

$$f : \Omega \to \mathbb{T} \quad \text{with} \quad \Omega \subset \mathbb{R}^n$$

Views:

transparent, on-the-fly coordinate transformation

$$\begin{aligned} g : \Omega' \to \Omega \\ f \circ g = f' : \Omega' \to \mathbb{T} \end{aligned}$$

Converters:

transparent, on-the-fly value transformation

$$\begin{aligned} h : \mathbb{T} \to \mathbb{T}' \\ h \circ f = f' : \Omega \to \mathbb{T}' \end{aligned}$$

Virtualized Sample Access

```
RandomAccessibleInterval<UnsignedByteType> img;
```

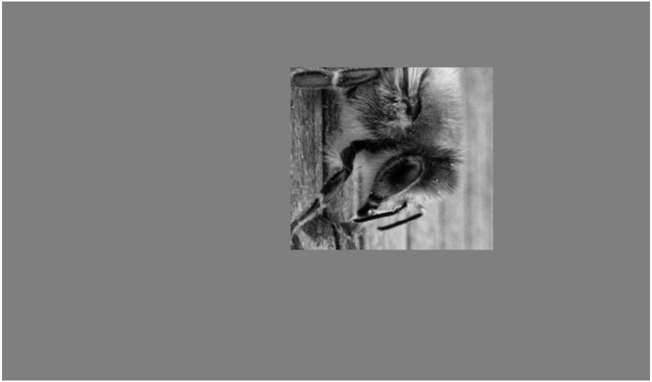
Virtualized Sample Access

```
Interval interval;
RandomAccessibleInterval<UnsignedByteType> cropped =
  Views.offsetInterval(img, interval);
```

Virtualized Sample Access

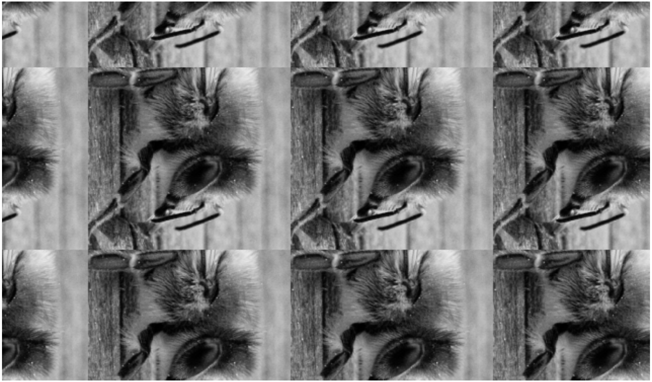
```
RandomAccessibleInterval<UnsignedByteType> rotated =
  Views.rotate(cropped, 0, 1);
```

Virtualized Sample Access



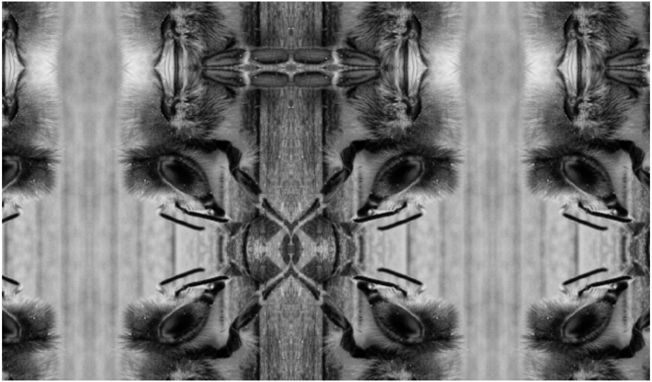
```
RandomAccessible<UnsignedByteType> extended =
  Views.extendValue(rotated, new UnsignedByteType(127));
```

Virtualized Sample Access



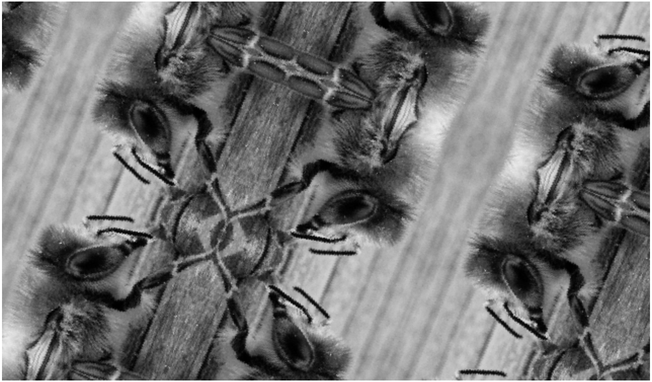
```
RandomAccessible<UnsignedByteType> extended =
  Views.extendPeriodic(rotated);
```

Virtualized Sample Access



```
RandomAccessible<UnsignedByteType> extended =
  Views.extendMirrorSingle(rotated);
```

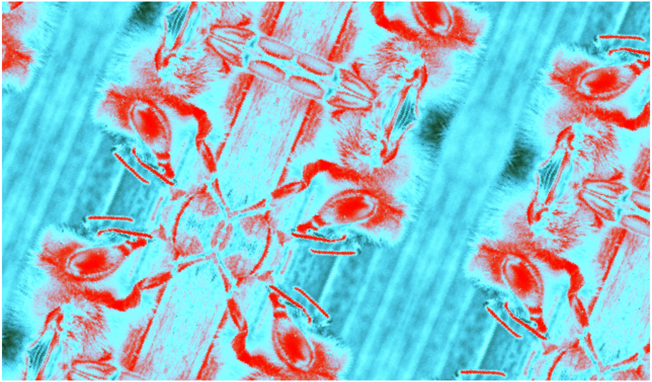
Virtualized Sample Access



```
RealRandomAccessible<UnsignedByteType> interpolated =
  Views.interpolate(extended,
    new NearestNeighborInterpolatorFactory<UnsignedByteType>());

AffineTransform affine;
RandomAccessible<UnsignedByteType> transformed =
  RealViews.affine(interpolated, affine);
```

Virtualized Sample Access



```
Converter<UnsignedByteType, ARGBType> lut;
RandomAccessible<ARGBType> converted =
  Converters.convert(transformed, lut, new ARGBType());
```

Performance Benchmarks

- Trivial operation: Invert all pixels
    - Iterate over all pixel (values).
- Complex operation: Compute center of mass
    - Sum *n*D coordinates weighted by pixel values.
    - Access coordinates and values.

- Java primitive type arrays (`byte[]/float[]`)
- ImageJ ImagePlus
- ImgLib2 ArrayImg
- ImgLib2 CellImg
- templated C++

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- ImageJ ImagePlus
- ImgLib2 ArrayImg
- ImgLib2 CellImg
- templated C++

Benchmark A: trivial operation

Java primitive array

```java
private static void invert(final float[] img) {
  for (int i = 0; i < img.length; i++) {
    img[i] = -img[i];
  }
}
```

Benchmark A: trivial operation

ImageJ

```java
private static void invert(final ImagePlus imp) {
  final ImageStack stack = imp.getStack();
  final int numSlices = stack.getSize();
  for (int s = 1; s <= numSlices; ++s) {
    final ImageProcessor ip = stack.getProcessor(s);
    final int size = ip.getPixelCount();
    for (int i = 0; i < size; i++)
      ip.setf(i, -ip.getf(i));
  }
}
```

Benchmark A: trivial operation

ImgLib2

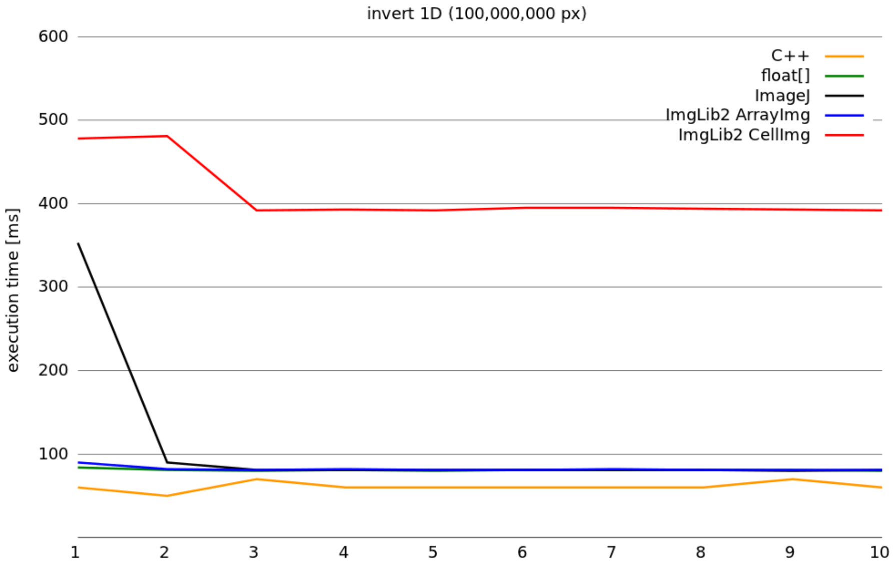
```java
static private <T extends RealType<T>> void invert(
    final IterableInterval<T> img) {
  for (final T t : img)
    t.mul(-1);
}
```

Benchmark A: trivial operation

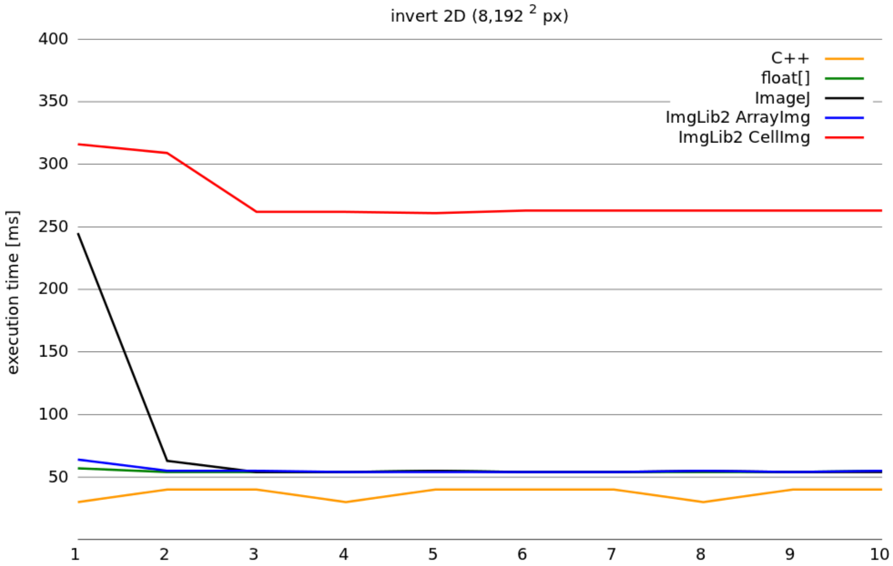
C++

```cpp
template<class T>
void invert(T* img, unsigned long long size) {
  for (unsigned long long i = 0; i < size; ++i) {
    img[i] = -img[i];
  }
}
```

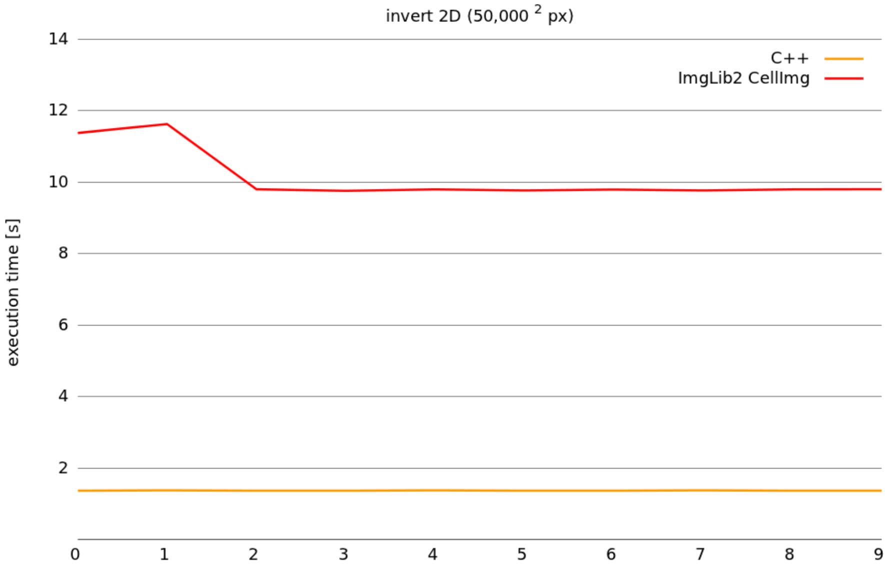
Benchmark A: trivial operation



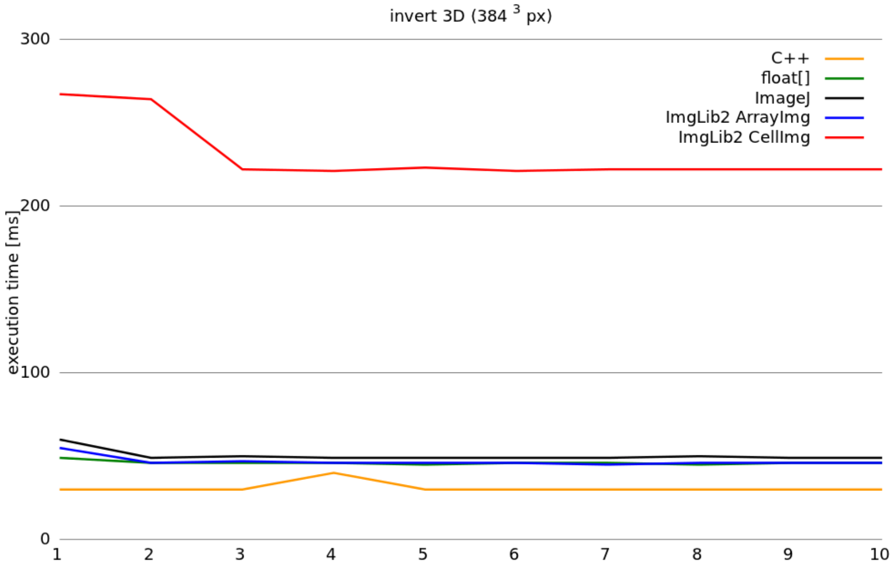
Benchmark A: trivial operation



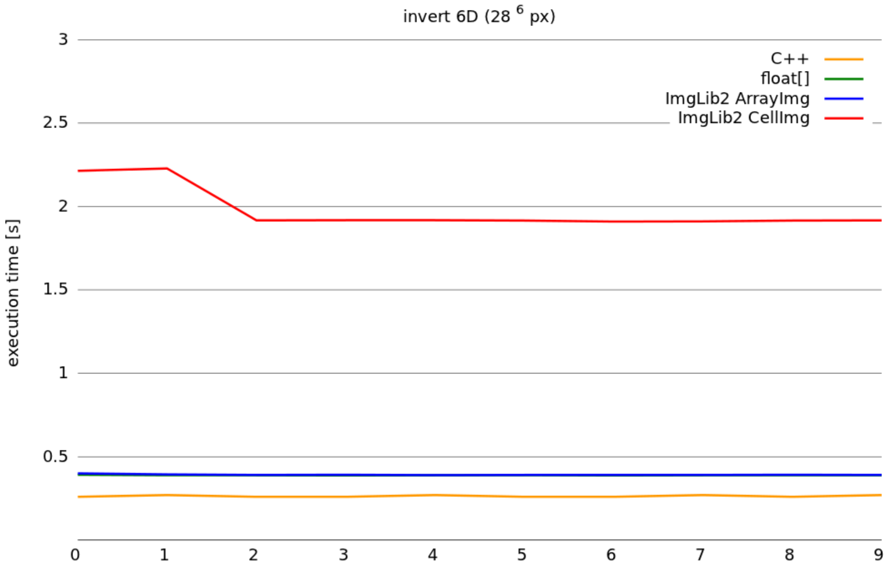
Benchmark A: trivial operation



Benchmark A: trivial operation



Benchmark A: trivial operation



Benchmark B: complex operation

Java primitive array (1D)

```java
private static double[] centerOfMass(
    final byte[] img, final int s0) {
  final RealSum c0 = new RealSum(), sum = new RealSum();
  for (int d0 = 0; d0 < s0; ++d0) {
    final double value = img[d0] & 0xff;
    c0.add(value * d0);
    sum.add(value);
  }
  final double s = sum.getSum();
  return new double[] { c0.getSum() / s };
}
```

Benchmark B: complex operation

Java primitive array (2D)

```java
private static double[] centerOfMass(
    final byte[] img, final int s0, final int s1) {
  final RealSum c0 = new RealSum(), c1 = new RealSum(),
      sum = new RealSum();
  int i = 0;
  for (int d1 = 0; d1 < s1; ++d1)
    for (int d0 = 0; d0 < s0; ++d0) {
      final double value = img[i++] & 0xff;
      c0.add(value * d0);
      c1.add(value * d1);
      sum.add(value);
    }
  final double s = sum.getSum();
  return new double[] { c0.getSum() / s, c1.getSum() / s };
}
```

Benchmark B: complex operation

Java primitive array (3D)

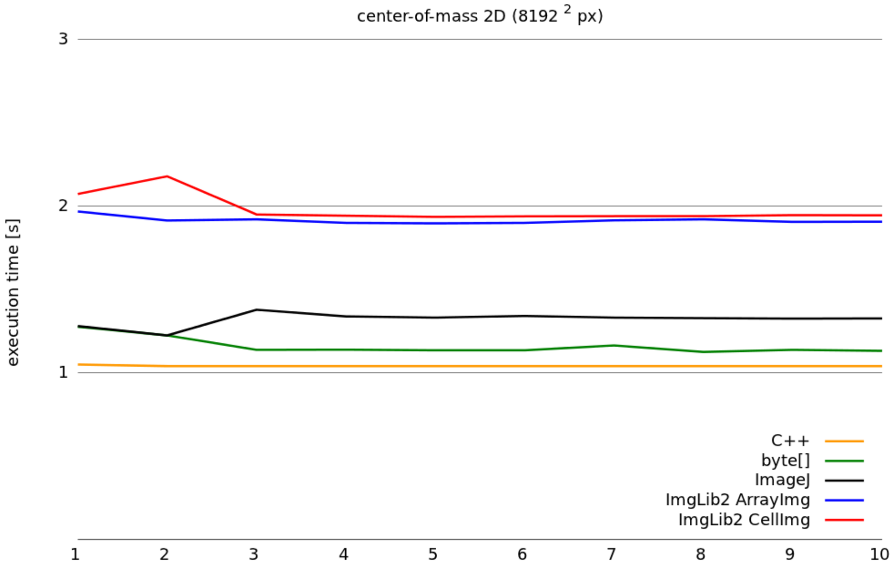
```java
private static double[] centerOfMass(
    final byte[] img, final int s0, final int s1, final int s2) {
  final RealSum c0 = new RealSum(), c1 = new RealSum(),
      c2 = new RealSum(), sum = new RealSum();
  int i = 0;
  for (int d2 = 0; d2 < s2; ++d2)
    for (int d1 = 0; d1 < s1; ++d1)
      for (int d0 = 0; d0 < s0; ++d0) {
        final double value = img[i++] & 0xff;
        c0.add(value * d0);
        c1.add(value * d1);
        c2.add(value * d2);
        sum.add(value);
      }
  final double s = sum.getSum();
  return new double[] {
      c0.getSum() / s, c1.getSum() / s, c2.getSum() / s };
}
```

Benchmark B: complex operation

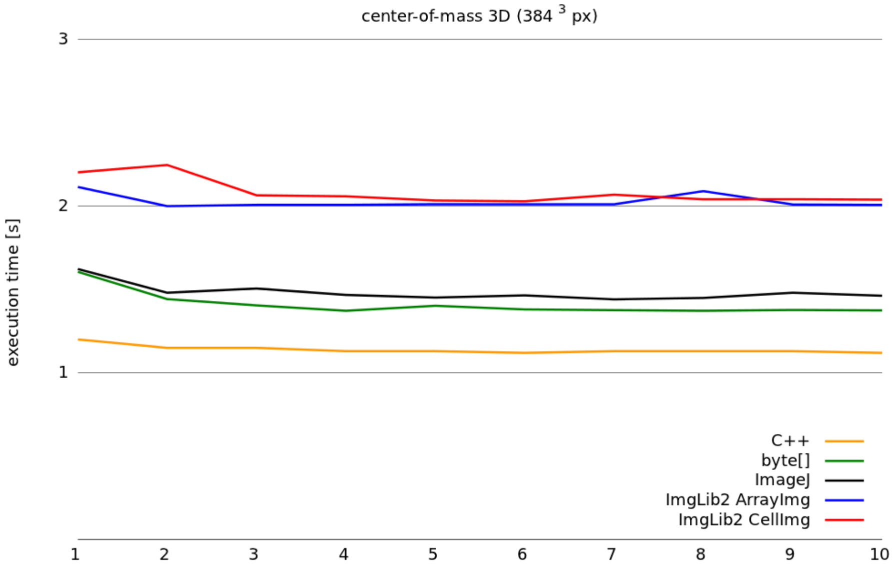
ImgLib2

```java
static private <T extends RealType<T>> double[] centerOfMass(
    final IterableInterval<T> img) {
  final RealSum[] c = new RealSum[img.numDimensions()];
  for (int d = 0; d < c.length; ++d)
    c[d] = new RealSum();
  final RealSum s = new RealSum();
  final Cursor<T> cursor = img.localizingCursor();
  while (cursor.hasNext()) {
    final double value = cursor.next().getRealDouble();
    s.add(value);
    for (int d = 0; d < c.length; ++d)
      c[d].add(cursor.getDoublePosition(d) * value);
  }
  final double[] centerOfMass = new double[c.length];
  final double sum = s.getSum();
  for (int d = 0; d < c.length; ++d)
    centerOfMass[d] = c[d].getSum() / sum;
  return centerOfMass;
}
```

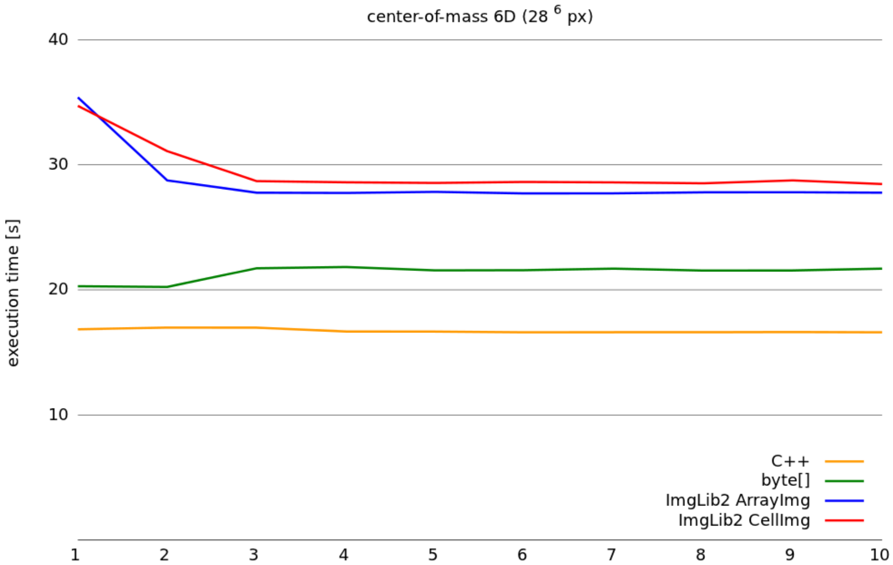
Benchmark B: complex operation



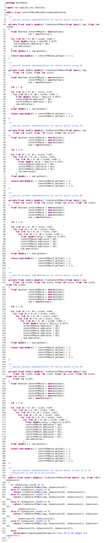
Benchmark B: complex operation



Benchmark B: complex operation

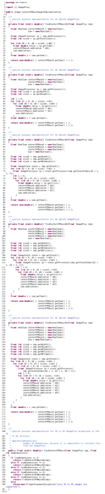


Benchmark B: complex operation



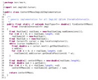
```java
package benchmark;

import net.imglib2.util.RealSum;

public class CenterOfMassByteNativeImplementation
{
  /**
   * special purpose implementation for native byte[] array 1D.
   */
  private final static double[] findCenterOfMass(final byte[] img, final int
size0)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  sum = new RealSum();

    for (int d0 = 0; d0 < size0; ++d0) {
      final double value = img[d0] & 0xff;
      centerOfMass0.add(value * d0);
      sum.add(value);
    }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s };
  }

  /**
   * special purpose implementation for native byte[] array 2D.
   */
  private final static double[] findCenterOfMass(final byte[] img,
      final int size0, final int size1)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  sum = new RealSum();

    int i = 0;

    for (int d1 = 0; d1 < size1; ++d1)
      for (int d0 = 0; d0 < size0; ++d0) {
        final double value = img[i++] & 0xff;
        centerOfMass0.add(value * d0);
        centerOfMass1.add(value * d1);
        sum.add(value);
      }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s };
  }

  /**
   * special purpose implementation for native byte[] array 3D.
   */
  private final static double[] findCenterOfMass(final byte[] img,
      final int size0, final int size1, final int size2)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  centerOfMass2 = new RealSum(),
                  sum = new RealSum();

    int i = 0;

    for (int d2 = 0; d2 < size2; ++d2)
      for (int d1 = 0; d1 < size1; ++d1)
        for (int d0 = 0; d0 < size0; ++d0) {
          final double value = img[i++] & 0xff;
          centerOfMass0.add(value * d0);
          centerOfMass1.add(value * d1);
          centerOfMass2.add(value * d2);
          sum.add(value);
        }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s,
                          centerOfMass2.getSum() / s };
  }

  /**
   * special purpose implementation for native byte[] array 4D.
   */
  private final static double[] findCenterOfMass(final byte[] img,
      final int size0, final int size1, final int size2, final int size3)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  centerOfMass2 = new RealSum(),
                  centerOfMass3 = new RealSum(),
                  sum = new RealSum();

    int i = 0;

    for (int d3 = 0; d3 < size3; ++d3)
      for (int d2 = 0; d2 < size2; ++d2)
        for (int d1 = 0; d1 < size1; ++d1)
          for (int d0 = 0; d0 < size0; ++d0) {
            final double value = img[i++] & 0xff;
            centerOfMass0.add(value * d0);
            centerOfMass1.add(value * d1);
            centerOfMass2.add(value * d2);
            centerOfMass3.add(value * d3);
            sum.add(value);
          }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s,
                          centerOfMass2.getSum() / s,
                          centerOfMass3.getSum() / s };
  }

  /**
   * special purpose implementation for native byte[] array 5D.
   */
  private final static double[] findCenterOfMass(final byte[] img,
      final int size0, final int size1, final int size2, final int size3,
final int size4)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  centerOfMass2 = new RealSum(),
                  centerOfMass3 = new RealSum(),
                  centerOfMass4 = new RealSum(),
                  sum = new RealSum();

    int i = 0;

    for (int d4 = 0; d4 < size4; ++d4)
      for (int d3 = 0; d3 < size3; ++d3)
        for (int d2 = 0; d2 < size2; ++d2)
          for (int d1 = 0; d1 < size1; ++d1)
            for (int d0 = 0; d0 < size0; ++d0) {
              final double value = img[i++] & 0xff;
              centerOfMass0.add(value * d0);
              centerOfMass1.add(value * d1);
              centerOfMass2.add(value * d2);
              centerOfMass3.add(value * d3);
              centerOfMass4.add(value * d4);
              sum.add(value);
            }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s,
                          centerOfMass2.getSum() / s,
                          centerOfMass3.getSum() / s,
                          centerOfMass4.getSum() / s };
  }

  /**
   * special purpose implementation for native byte[] array 6D.
   */
  private final static double[] findCenterOfMass(final byte[] img,
      final int size0, final int size1, final int size2, final int size3,
final int size4,
      final int size5)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  centerOfMass2 = new RealSum(),
                  centerOfMass3 = new RealSum(),
                  centerOfMass4 = new RealSum(),
                  centerOfMass5 = new RealSum(),
                  sum = new RealSum();

    int i = 0;

    for (int d5 = 0; d5 < size5; ++d5)
      for (int d4 = 0; d4 < size4; ++d4)
        for (int d3 = 0; d3 < size3; ++d3)
          for (int d2 = 0; d2 < size2; ++d2)
            for (int d1 = 0; d1 < size1; ++d1)
              for (int d0 = 0; d0 < size0; ++d0) {
                final double value = img[i++] & 0xff;
                centerOfMass0.add(value * d0);
                centerOfMass1.add(value * d1);
                centerOfMass2.add(value * d2);
                centerOfMass3.add(value * d3);
                centerOfMass4.add(value * d4);
                centerOfMass5.add(value * d5);
                sum.add(value);
              }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s,
                          centerOfMass2.getSum() / s,
                          centerOfMass3.getSum() / s,
                          centerOfMass4.getSum() / s,
                          centerOfMass5.getSum() / s };
  }

  /**
   * special purpose implementation for native byte[] arrays 1D to 6D.
   * dispatches to the 1D to 6D versions.
   */
  public final static double[] findCenterOfMass(final byte[] img, final int[]
dimensions)
  {
    if (dimensions.length == 1)
      return findCenterOfMass(img, dimensions[0]);
    else if (dimensions.length == 2)
      return findCenterOfMass(img, dimensions[0], dimensions[1]);
    else if (dimensions.length == 3)
      return findCenterOfMass(img, dimensions[0], dimensions[1], dimensions
[2]);
    else if (dimensions.length == 4)
      return findCenterOfMass(img, dimensions[0], dimensions[1], dimensions
[2],
          dimensions[3]);
    else if (dimensions.length == 5)
      return findCenterOfMass(img, dimensions[0], dimensions[1], dimensions
[2],
          dimensions[3], dimensions[4]);
    else if (dimensions.length == 6)
      return findCenterOfMass(img, dimensions[0], dimensions[1], dimensions
[2],
          dimensions[3], dimensions[4], dimensions[5]);
    else
      throw new IllegalArgumentException("only 1D to 6D images are
supported");
  }
}
```

Java `byte[]` (1D-6D)



```java
package benchmark;

import ij.ImagePlus;

public class CenterOfMassImageJImplementation
{
  /**
   * special purpose implementation for 1D {@link ImagePlus}.
   */
  private final static double[] findCenterOfMass1D(final ImagePlus imp)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  sum = new RealSum();

    final ImageProcessor ip = imp.getProcessor();
    final int size0 = ip.getPixelCount();

    for (int d0 = 0; d0 < size0; ++d0) {
      final double value = ip.getf(d0);
      centerOfMass0.add(value * d0);
      sum.add(value);
    }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s };
  }

  /**
   * special purpose implementation for 2D {@link ImagePlus}.
   */
  private final static double[] findCenterOfMass2D(final ImagePlus imp)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  sum = new RealSum();

    final ImageProcessor ip = imp.getProcessor();
    final int size0 = ip.getWidth();
    final int size1 = ip.getHeight();

    int i = 0;
    for (int d1 = 0; d1 < size1; ++d1)
      for (int d0 = 0; d0 < size0; ++d0) {
        final double value = ip.getf(i++);
        centerOfMass0.add(value * d0);
        centerOfMass1.add(value * d1);
        sum.add(value);
      }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s };
  }

  /**
   * special purpose implementation for 3D {@link ImagePlus}.
   */
  private final static double[] findCenterOfMass3D(final ImagePlus imp)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  centerOfMass2 = new RealSum(),
                  sum = new RealSum();

    final int size0 = imp.getWidth();
    final int size1 = imp.getHeight();
    final int size2 = imp.getNChannels();

    final ImageStack stack = imp.getStack();
    for (int d2 = 0; d2 < size2; ++d2) {
      final ImageProcessor ip = stack.getProcessor(imp.getStackIndex(d2 + 1,
1, 1));
      int i = 0;
      for (int d1 = 0; d1 < size1; ++d1)
        for (int d0 = 0; d0 < size0; ++d0) {
          final double value = ip.getf(i++);
          centerOfMass0.add(value * d0);
          centerOfMass1.add(value * d1);
          centerOfMass2.add(value * d2);
          sum.add(value);
        }
    }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s,
                          centerOfMass2.getSum() / s };
  }

  /**
   * special purpose implementation for 4D {@link ImagePlus}.
   */
  private final static double[] findCenterOfMass4D(final ImagePlus imp)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  centerOfMass2 = new RealSum(),
                  centerOfMass3 = new RealSum(),
                  sum = new RealSum();

    final int size0 = imp.getWidth();
    final int size1 = imp.getHeight();
    final int size2 = imp.getNChannels();
    final int size3 = imp.getNSlices();

    final ImageStack stack = imp.getStack();
    for (int d3 = 0; d3 < size3; ++d3) {
      for (int d2 = 0; d2 < size2; ++d2) {
        final ImageProcessor ip = stack.getProcessor(imp.getStackIndex(d2 +
1, d3 + 1, 1));
        int i = 0;
        for (int d1 = 0; d1 < size1; ++d1)
          for (int d0 = 0; d0 < size0; ++d0) {
            final double value = ip.getf(i++);
            centerOfMass0.add(value * d0);
            centerOfMass1.add(value * d1);
            centerOfMass2.add(value * d2);
            centerOfMass3.add(value * d3);
            sum.add(value);
          }
      }
    }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s,
                          centerOfMass2.getSum() / s,
                          centerOfMass3.getSum() / s };
  }

  /**
   * special purpose implementation for 5D {@link ImagePlus}.
   */
  private final static double[] findCenterOfMass5D(final ImagePlus imp)
  {
    final RealSum centerOfMass0 = new RealSum(),
                  centerOfMass1 = new RealSum(),
                  centerOfMass2 = new RealSum(),
                  centerOfMass3 = new RealSum(),
                  centerOfMass4 = new RealSum(),
                  sum = new RealSum();

    final int size0 = imp.getWidth();
    final int size1 = imp.getHeight();
    final int size2 = imp.getNChannels();
    final int size3 = imp.getNSlices();
    final int size4 = imp.getNFrames();

    final ImageStack stack = imp.getStack();
    for (int d4 = 0; d4 < size4; ++d4) {
      for (int d3 = 0; d3 < size3; ++d3) {
        for (int d2 = 0; d2 < size2; ++d2) {
          final ImageProcessor ip = stack.getProcessor(
              imp.getStackIndex(d2 + 1, d3 + 1, d4 + 1));
          int i = 0;
          for (int d1 = 0; d1 < size1; ++d1)
            for (int d0 = 0; d0 < size0; ++d0) {
              final double value = ip.getf(i++);
              centerOfMass0.add(value * d0);
              centerOfMass1.add(value * d1);
              centerOfMass2.add(value * d2);
              centerOfMass3.add(value * d3);
              centerOfMass4.add(value * d4);
              sum.add(value);
            }
        }
      }
    }
    final double s = sum.getSum();

    return new double[] { centerOfMass0.getSum() / s,
                          centerOfMass1.getSum() / s,
                          centerOfMass2.getSum() / s,
                          centerOfMass3.getSum() / s,
                          centerOfMass4.getSum() / s };
  }

  /**
   * special purpose implementation for 1D to 5D ImagePlus dispatches to the
1D
   * to 5D versions.
   *
   * @param numDimensions
   *          number of dimensions, because it is impossible to retrieve this
   *          from the ImagePlus.
   */
  public final static double[] findCenterOfMass(final ImagePlus imp, final
int numDimensions)
  {
    if (numDimensions == 1)
      return findCenterOfMass1D(imp);
    else if (numDimensions == 2)
      return findCenterOfMass2D(imp);
    else if (numDimensions == 3)
      return findCenterOfMass3D(imp);
    else if (numDimensions == 4)
      return findCenterOfMass4D(imp);
    else if (numDimensions == 5)
      return findCenterOfMass5D(imp);
    else
      throw new IllegalArgumentException("only 1D to 5D images are
supported");
  }
}
```

ImageJ (1D-5D)



```java
package benchmark;

import net.imglib2.Cursor;

public class CenterOfMassImgLib2Implementation
{
  /**
   * generic implementation for all ImgLib2 {@link IterableInterval}s.
   */
  public final static <T extends RealType<T>> double[] findCenterOfMass(
      final IterableInterval<T> img)
  {
    final RealSum[] realSums = new RealSum[img.numDimensions()];
    for (int d = 0; d < realSums.length; ++d)
      realSums[d] = new RealSum();
    final RealSum s = new RealSum();
    final Cursor<T> cursor = img.localizingCursor();
    while (cursor.hasNext()) {
      final double w = cursor.next().getRealDouble();
      s.add(w);
      for (int d = 0; d < realSums.length; ++d)
        realSums[d].add(cursor.getDoublePosition(d) * w);
    }

    final double[] centerOfMass = new double[realSums.length];
    final double sum = s.getSum();
    for (int d = 0; d < realSums.length; ++d)
      centerOfMass[d] = realSums[d].getSum() / sum;

    return centerOfMass;
  }
}
```

ImgLib2
(arbitrary type, container, dimensionality)

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Contributors:

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`http://imglib2.net/`

Pietzsch, T., Preibisch, S., Tomančák, P., and Saalfeld, S.
“ImgLib2 – generic image processing in Java,”
Bioinformatics (September 2012).