Milena: Write Generic Morphological Algorithms Once, Run on Many Kinds of Images

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International Symposium on Mathematical Morphology (ISMM)

Groningen, The Netherlands – August 24 - 27, 2009

Intent

Context

- Software solutions for Mathematical Morphology (MM).
- Reusability, flexibility (and efficiency).

Aim of this talk

- Think Generic!
- Advertise about a generic software framework proposal.

Genericity in MM at a Glance

Wouldn't it be nice to be able to implement an algorithm like this?

```
for_all(p)
  {
    sup = input(p);
    for_all(q)
      sup.take(input(q));
    output(p) = sup;
  }
```

Go to full code

Generic code: works on every kind of compatible images.

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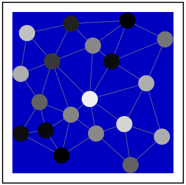

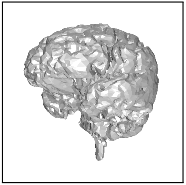

Observations and Reflections

Observations

- Writing reusable MM software with good properties is hard.
- Even harder if you want to preserve other traits such as ease-of-use, efficiency, readability and flexibility.

Reflections

- Where should we start if we wanted to achieve the (impossible) goal of writing MM for all users and applications?
- Idea: Start with a core component with good features, and then build tools on top of it.
- What core?

The Nature of the Core

This core shall be:

- General enough to serve a reusable basis.
- Good enough to be used as-is.
- Accessible to all MM users.
- Extensible.
- Compatible with today's systems.

→ A generic library.

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Implementing Mathematical Morphology Algorithms

A Very Simple Operator

Let's consider the morphological dilation of an image I with a flat structuring element B.
A mathematical definition:

$$\delta_B(I)(x) = \sup_{h \in B} I(x + h)$$

where

- I is a function $D \rightarrow V$ associating a point from the domain D to a value from the set V.
- B is a structuring element.

A Non Generic Implementation

```
for (unsigned int r = 0; r < input.nrows(); ++r)
  for (unsigned int c = 0; c < input.ncols(); ++c) {
    unsigned char sup = input(r, c);
    if (input(r-1, c) > sup) sup = input(r-1, c);
    if (input(r+1, c) > sup) sup = input(r+1, c);
    if (input(r, c-1) > sup) sup = input(r, c-1);
    if (input(r, c+1) > sup) sup = input(r, c+1);
    output(r, c) = sup;
  }
```

This solution makes a few hypotheses:

1. The image is 2-dimensional.
2. Points have nonnegative integers coordinates starting at 0.
3. Values have to be compatible with the 8-bit `unsigned char` type.
4. The values of the image form a totally ordered set.
5. The structuring element is based on the 4-connectivity.

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A Non Generic Implementation: Some Limitations

This code cannot handle (as-is) any of the following variations:

1. The input is a 3-dimensional image.
2. Its points are located on a box subset of a floating-point grid.
3. The values are encoded as 12-bit integers or as floating-point numbers.
4. The image is multivalued (e.g., a 3-channel color image).
5. The structuring element represents an 8-connectivity.

Though less common, images with these features can be found in fields like biomedical imaging, astronomy, document image analysis or arts.

A Non Generic Implementation: More Limitations

What if…

- …the domain D of I…
  - …is not an hyperrectangle (a "box")?
  - …is not a set of points located in a geometrical space, but a 3D triangle mesh?
  - …is a restriction (subset) of another image's domain?
- …the neighbors of a site are not expressed with a fixed-set structuring element, but through a function associating a set of sites to any site of the image?
- …the values are not scalar, nor vectorial (e.g., diffusion tensors)?

Back to the Generic Implementation

```
for_all(p)
  {
    sup = input(p);
    for_all(q)
      sup.take(input(q));
    output(p) = sup;
  }
```

where

- p $\in D$
- q $\in$ win(p)
- sup is a small object (accumulator) computing the supremum of a set of values.

A Generic Implementation: Benefits

```
for_all(p)
  {
    sup = input(p);
    for_all(q)
      sup.take(input(q));
    output(p) = sup;
  }
```

A few remarks:

- Small yet readable.
- Not tied to specific image type, i.e, generic.
- Example: dilating an image I where
  - $D(I) =$ a Region Adjacency Graph (RAG) where each site is a region of another image J.
  - $V(I) = \mathbb{R}^n$ (n-dimensional vectors expressing features from each underlying region of J).
  - $\forall$p, q browses the sites (i.e., regions) adjacent to p.

Introducing Genericity in MM

Main Idea

- MM software should be generic [Köthe, 1999, Darbon et al., 2002, d'Ornellas and van den Boomgaard, 2003].

Modus Operandi

- Genericity is possible provided abstractions of concepts of the domain are well defined.
- In Object-Oriented Programming (OOP), these abstractions are called interfaces.

Genericity in Mathematical Morphology

A Generic Definition of the Concept of Image

Definition

An image I is a function from a domain D to a set of values V. The elements of D are called the sites of I, while the elements of V are its values.

For the sake of generality, we use the term site instead of point.

Abstractions in Generic Programming

With Generic Programming (GP):

- Algorithms are no longer defined in terms of features specific to an image type.

```
for (unsigned int r = 0; r < input.nrows(); ++r)
  for (unsigned int c = 0; c < input.ncols(); ++c)
    ...
```

- Instead, abstractions are used.

```
mln_piter(I) p(input.domain()); // 'p' is a site iterator.
for_all(p)                      // ∀p ...
  ...
```

The Image Abstraction

The interface of an image type includes:

- Associated types.

```
typedef domain_t;  // Type of the domain (site set).
typedef site;      // Type of a site.
typedef piter;     // Associated iterator type
typedef value;     // Type of a value.
typedef vset;      // Type of the set of values.
```

- Methods (services provided by the image).

```
value operator()(site p);  // ‘ima(p)’ → value
bool has(site p);          // Does ‘p’ belongs to ‘ima’?
vset values();             // Return the domain (D).
domain_t domain();         // Return the value set (V).
```

Other Abstractions

Site_Set Sets of sites must respect this interface.

```
typedef site;        // The type of the sites.
typedef fwd_piter;   // Forward iterator on the set's sites.
typedef bkd_piter;   // Backward iterator on the set's sites.

bool has(psite p);   // Does 'p' belongs to this set?
```

Also: Point_Site, Delta_Point_Site, Site_Iterator, Value, Value_Set, Value_Iterator, Neighborhood, Window, Weighted_Window, Accumulator, Function, ...

Introducing Milena

Good News

- The previous concepts can be translated to actual, working C++ code almost as-is.
- They have been implemented as a library (core component).
- Plus many, many more tools.

Milena

- A generic and efficient C++ library [Géraud and Levillain, 2008].
- Released within the Olena 1.0 platform.

Milena

What is in Milena?

- Abstractions
- Data structures, in particular site sets.
- Many image types (and their associated types), mostly built upon classical site sets (domains). E.g.:
  - Box on a regular 2D grid → `image2d`
  - Undirected graph → $\left\{ \begin{array}{l} \text{image with values on vertices.} \\ \text{image with values on edges.} \end{array} \right.$
- Many auxiliary tools to make it easy to use and write algorithms (macros, accumulators, functions, etc.).
- Algorithms, in particular (but not only) in the field of on MM.

Site Sets

- Convey a lot of structural and topological information.
- Classical cases: hyperrectangles (boxes) on regular *n*-dimensional grids.
- But also: unstructured site sets based on usual data structures:
  - Arrays.
  - Sets.
  - Priority queues.
  - Hybrid containers.
  - etc.
- (Undirected) Graphs.
- Complexes.

Site Sets: Complexes

Definition

A simplicial complex is “a set of simplices”, where a simplex is the simplest manifold that can be created using *n* points.

- A 0-simplex ≡ a point.
- A 1-simplex ≡ a line segment.
- A 2-simplex ≡ a triangle.
- A 3-simplex ≡ a tetrahedron.

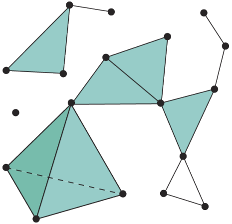

Figure: A simplicial 3-complex.

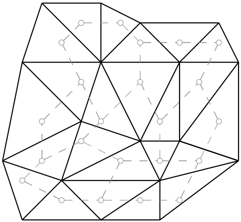

Figure: A simplicial 2-complex (mesh).

Site Sets: Complexes (cont.)

Ideal framework to process mesh-based "images".

Figure: Triangle mesh, seen as a simplicial 2-complex.

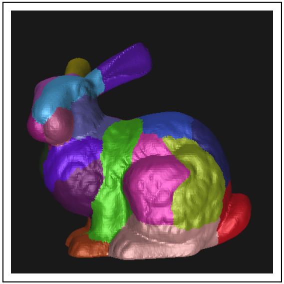

Figure: Watershed-based segmentation using curvature computed on edges [Meyer, 1991, Cousty et al., 2008].

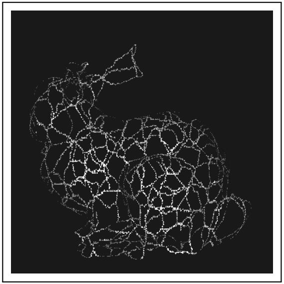

Figure: Skeleton using breadth-first thinning based on simple point characterization [Couprie and Bertrand, 2009].

Site Sets: More

- Milena's implementation of complexes is flexible enough to implement many structures: cubical complexes, simplicial complexes, etc.
- Providers can add new structures (either generic or not) to Milena and benefiting from the framework of the library (reuse algorithms, accumulators, etc.).
- Milena introduces no actual additional (run time/space/development) cost in itself.

Even More: Morphers

- Morphers: lightweight objects producing an image from an image.
- Kind of a function on an image.
- Example: Dilation by a 4-c structuring element:

```
dilation(ima, win_c4p());
```

- Likewise, but restricting the domain of `ima` to the subset `s`:

```
dilation(ima | s, win_c4p());
```

- Dilation of the red channel of an RGB color image:

```
dilation(red << rgb_ima, win_c4p());
```

- Many morphers provided by Milena: wrapping an image (torus), stacking several images, taking a 2D slice from a 3D volume, applying a geometrical transformation, etc.

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A Simple Milena Processing Chain

- A generic code:

```
closed = morpho::closing::area(ima, nbh, lambda);
wshed  = morpho::watershed::flooding(closed, nbh, nb);
```

Go to full code

- Inputs:

  `ima` Input image (e.g, `image2d<int>`, `image3d<float>`, `complex_image`, etc.)

  `nbh` Neighborhood (e.g., `c4`, `c26`, `adjacent_vertices_neighborhood`, etc.).

  `lambda` Value of the criterion (integer).

- Applicable to many different image types as-is.

Results (2D Image, 6-connectivity)

Figure: "Classical" image, with 6-connectivity.

Figure: Magnitude of the gradient.

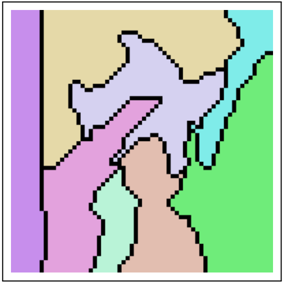

Figure: Result of the image processing chain on the magnitude of the gradient.

Results (Cubical 2-Complex)

Figure: Magnitude of the gradient computed on the edges of a cubical 2-complex.

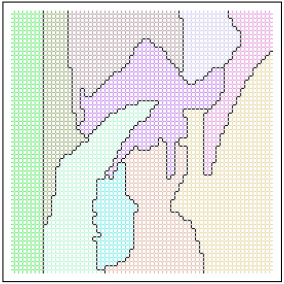

Figure: Result of the image processing chain.

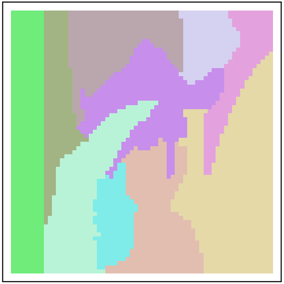

Figure: Extension of labels to 2-faces (squares) for visualization purpose.

Results (Graph)

Example of data clustering using MM methods.

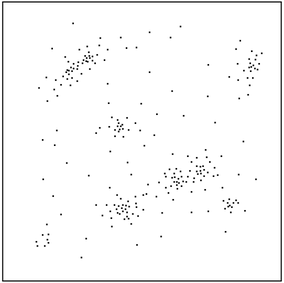

Figure: Vertices of a graph.

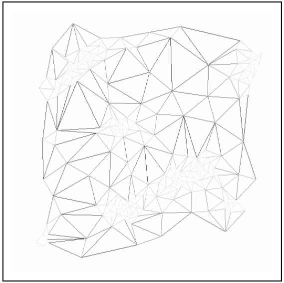

Figure: Distance-based magnitude computed on the edges of the triangulation of the graph.

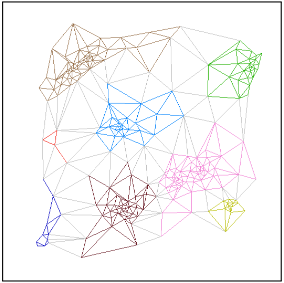

Figure: Result of the image processing chain on this magnitude.

Epilogue

The Present: Olena 1.0

- The latest version of Milena ships with the Olena 1.0 platform, released July 14, 2009.

  `http://olena.lrde.epita.fr`

- We invite you to download and try it.
- Olena is Free Software released under the GNU General Public License (GNU GPL).
- There is much more to say about Milena, in particular about efficiency.
- Send questions and comments to: olena@lrde.epita.fr.

The Future

- We are actively working on making the library easier to install, learn and use.
- Milena is the heart of the platform we are developing. We are working on adding
  - GUIs,
  - bridges to other languages (starting with Python),
  - command-line tools,
  - etc.

  while retaining as many advantage from Milena's core features as possible (namely genericity and efficiency).

Thank You!

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Full Code of the Dilation

```
template <typename I, typename W>
mln_concrete(I)
dilation(const I& input, const W& win)
{
  mln_concrete(I) output;
  initialize(output, input);
  mln_piter(I) p(input.domain());
  mln_qiter(W) q(win, p);
  for_all(p)
  {
    accu::supremum<mln_value(I)> sup = input(p);
    for_all(q) if (input.has(q))
      sup.take(input(q));
    output(p) = sup;
  }
  return output;
}
```

Go to simplified code

Actual Code of the Illustrations

```
template <typename L, typename I, typename N>
mln_ch_value(I, L)
chain(const I& ima, const N& nbh, int lambda, L& nb)
{
  mln_concrete(I) closed =
    morpho::closing::area(ima, nbh, lambda);
  return morpho::watershed::flooding(closed, nbh, nb);
}
```

Go to simplified code