MathVisionC++ for Efficient Medical Image Processing in Mathematica

Using a Mathlink Caching Scheme

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Introduction

Why use mathematica for (mathematical) image analysis?

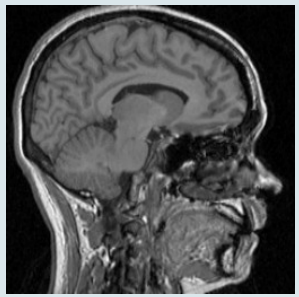
- Convenient for fast translation of Mathematics (e.g. analytical formulas) to numerical implementation (e.g. on pixel/voxel data)
- Implementing simple image processing algorithms is relatively fast
- Useful built-in functionality for visualizing results, for instance `ListDensityPlot` (not useful anymore in version 6), `ListContourPlot`, `ListContourPlot3D` etc.

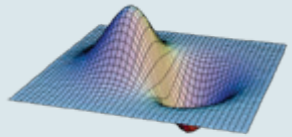
MathVisionTools

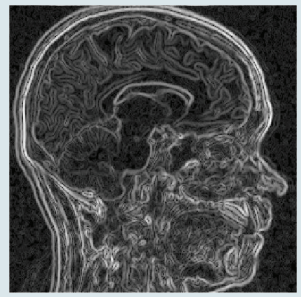
- MathVisionTools is a Mathematica library for image processing and analysis
- Including:
  - Differential Geometry (e.g. Gaussian derivatives for any order for N dimensions, Geometry driven diffusion)
  - Orientation analysis (e.g. Polar Fourier Transform, 2D Hankel Transform, G- convolutions, Stochastic Completion Kernels)
  - Visualization functions (e.g. for visualizing tensorial images)
  - Import / Export (e.g. of DICOM format)
- Optimized (fast) Mathematica code

Described in: B.M. ter Haar Romeny, M.A. van Almsick, *MathVisionTools: Medical Image Analysis Prototyping*, in Wolfram Technology Conference 2004; Editors: Wolfram, Champaign, Illinois, United States, 48-54, (2004)

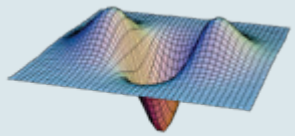
Example: Differential Invariants

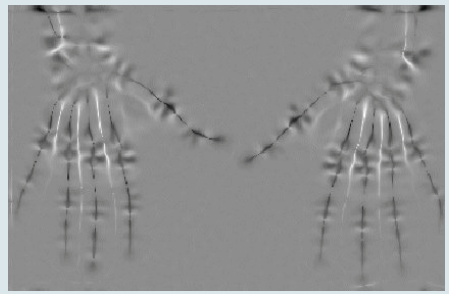




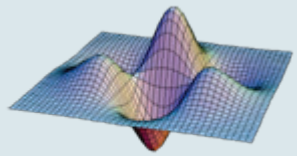


1st order (edges)





2nd order (ridges)



3rd order (T-junctions)

Expression for Rotation invariant T-junction detection:

$$\frac{1}{(L_x^2+L_y^2)^3}\left(-L_{xxy}L_y^5+L_y^4\left(2L_{xy}^2-L_x\left(L_{xxx}-2L_{xyy}\right)+L_{xx}L_{yy}\right)+\right.$$
$$L_x^4\left(2L_{xy}^2-L_xL_{xyy}+L_{xx}L_{yy}\right)+L_x^2L_y^2\left(3L_{xx}^2-8L_{xy}^2+L_x\left(-L_{xxx}+L_{xyy}\right)-4L_{xx}L_{yy}+3L_{yy}^2\right)+$$
$$\left.L_xL_y^3\left(6L_{xy}\left(L_{xx}-L_{yy}\right)+L_x\left(L_{xxy}-L_{yyy}\right)\right)+L_x^3L_y\left(6L_{xy}\left(-L_{xx}+L_{yy}\right)+L_x\left(2L_{xxy}-L_{yyy}\right)\right)\right)$$

Why Create a C++ Library?

Often large datasets and sophisticated algorithms

→Severe requirements on memory and processing power

→*Mathematica* can not meet these requirements

- Slow (interpreted language)
- Redundant memory consumption (can't specify datatypes)

Our goal: take advantage of the speed and efficiency of a C++ program and the advantages of *mathematica* at the same time

→ So: write the real function in C++ and provide interfaces in *Mathematica* through *Mathlink*

Problems with Mathlink

1. Data transfers are required
   ML-functions in C++ program
   ↔ Mathematica kernel
   Consumes a significant amount of time
   when working with large datasets
2. The provided Mathlink C interface is inconvenient

Solutions :

1 → Mathlink *caching* mechanism

2 → A C++ `MathLinkIO` class

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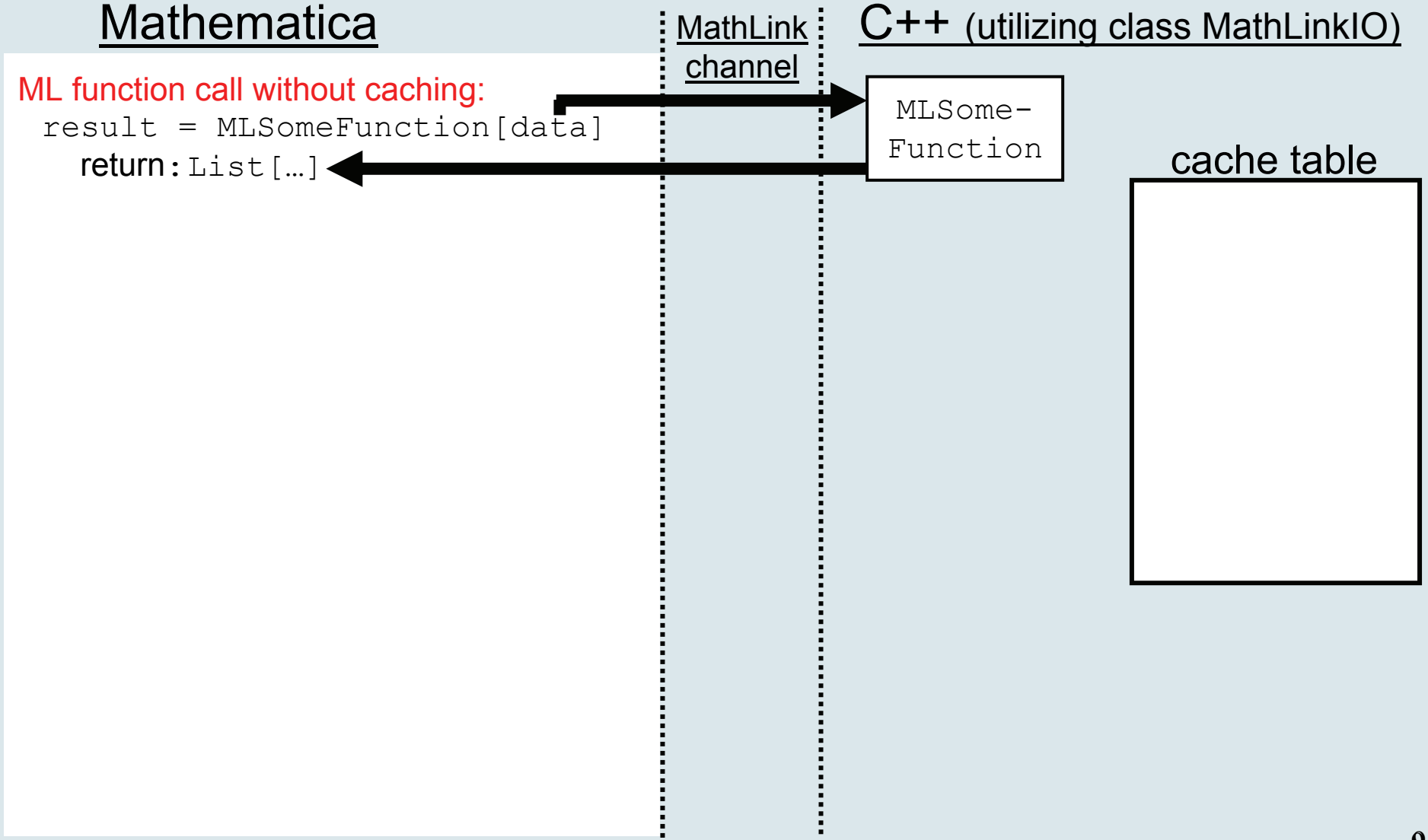
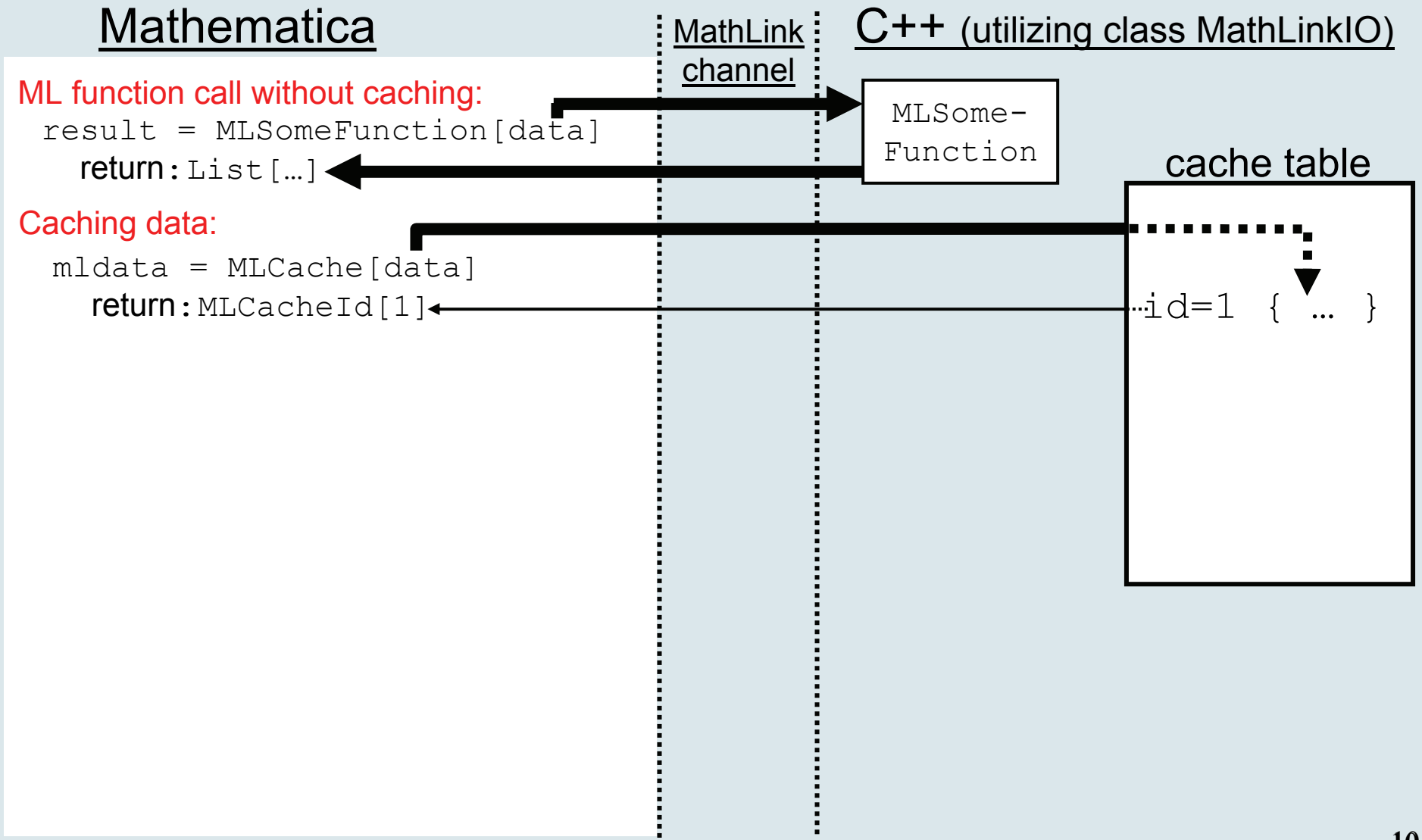
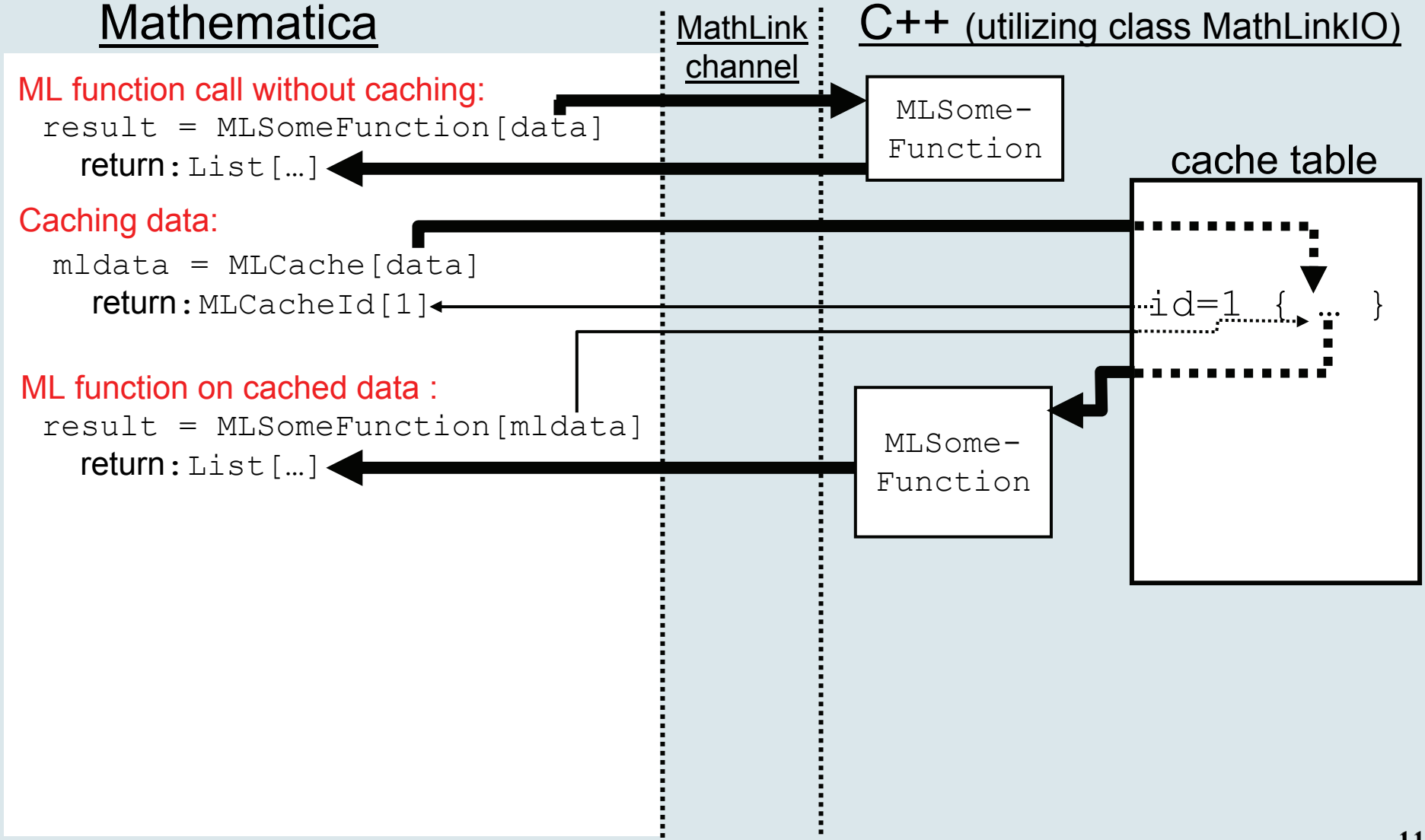
MathLink Caching Mechanism



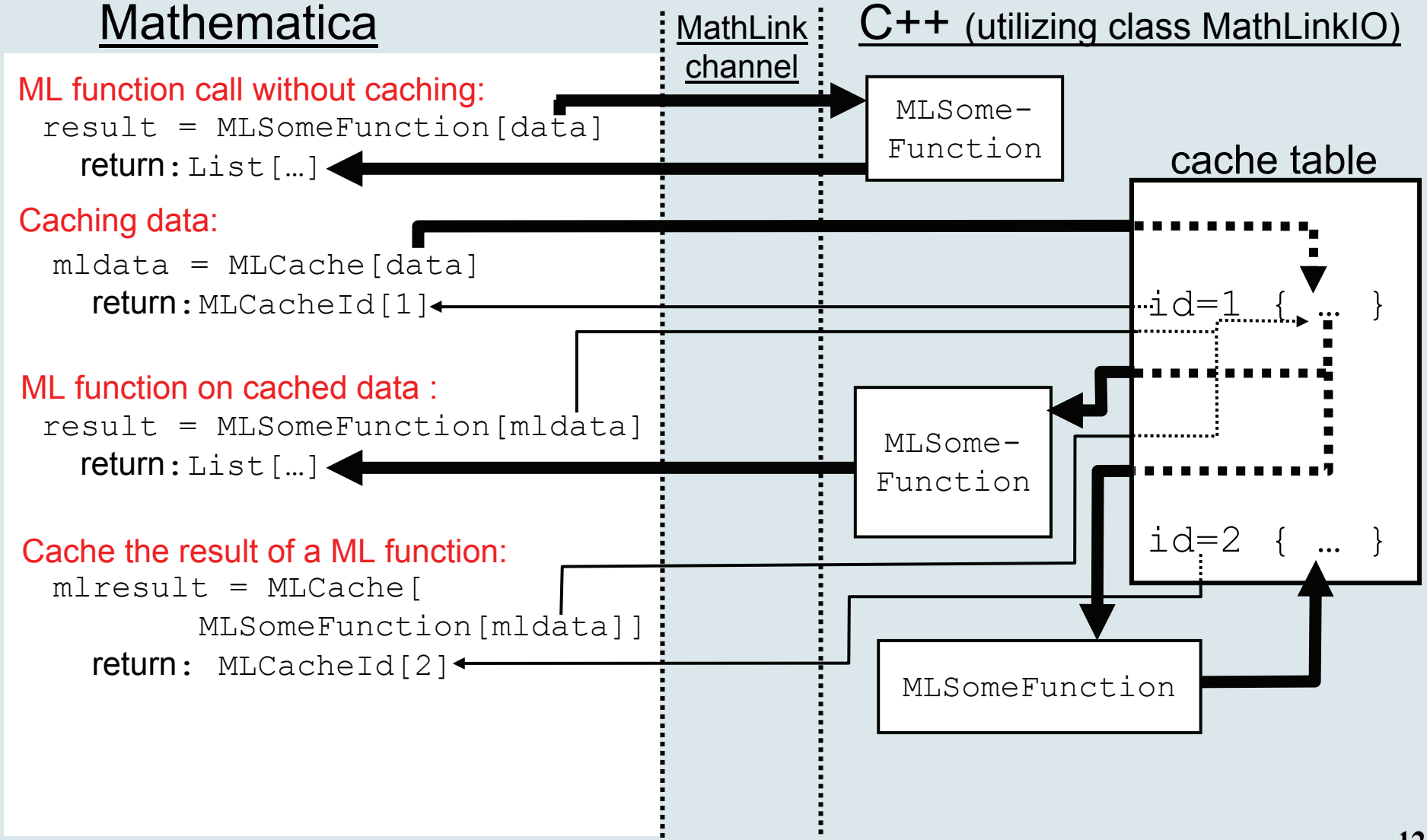
MathLink Caching Mechanism



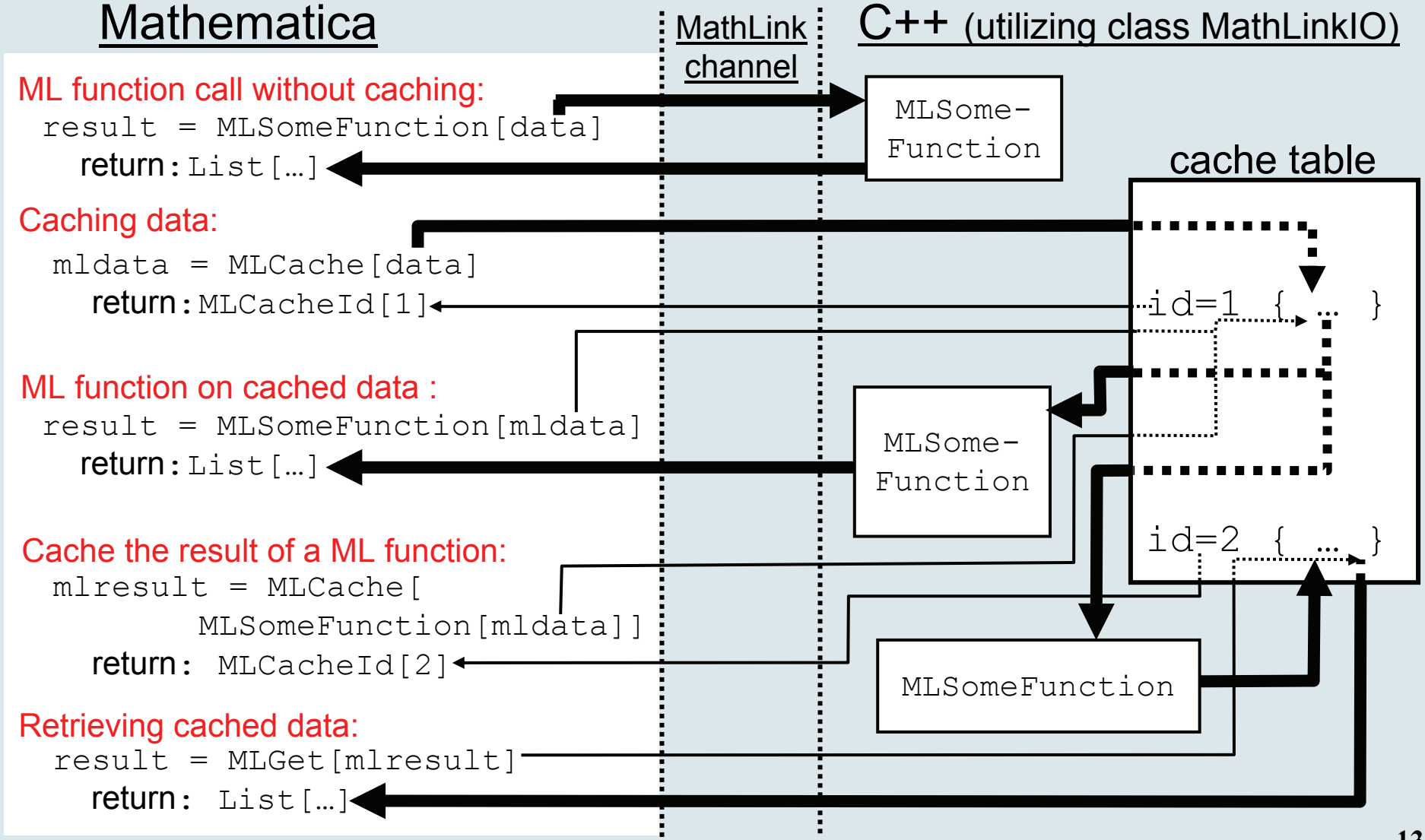
MathLink Caching Mechanism



MathLink Caching Mechanism



MathLink Caching Mechanism



Mathlink Caching Features

- All ML-functions can transparently handle real data and cached objects
- What type of data can we cache?
  → All *arrays* containing *numerical* data that Mathematica can store as *packed arrays*
- Additional mathematica functions for controlling the cache:
  - `MLRemove` and `MLRemoveAll` - to clear the cache
  - `MLCacheInfo` – to obtain information on the stored elements
  - `MLReplace[id, expr]` – to replace the data to which `id` (which should be an `MLCacheId`) points by `expr`. Useful to prevent "memory leak" in the cache when calling `MLCache` multiple times

Example run:

```
In[271]:= << MathVisionCpp`

In[272]:= mlimg = MLCache[img]

Out[272]= MLCacheId[1]

In[273]:= mlkrn = MLCache[krn]

Out[273]= MLCacheId[2]

In[274]:= MLCacheInfo[] // MatrixForm

Out[274]//MatrixForm=
        (MLCacheId[1]  {16, 16}  {List, List}  RealArray)
        (MLCacheId[2]  {5, 6}    {List, List}  RealArray)

In[275]:= mlresult = MLCache[MLListConvolve[mlkrn, mlomg, krncent, BOUNDARYCYCLIC, CONVOLVEDIRECT]]

        MathVisionCpp::invalidparams : Invalid parameter types used. Function aborted.

Out[275]= MLInvalidArgumentNumber[2]

In[276]:= mlresult = MLCache[MLListConvolve[mlkrn, mlimg, krncent, BOUNDARYCYCLIC, CONVOLVEDIRECT]]

Out[276]= MLCacheId[3]

In[277]:= result = MLGet[mlresult]; Dimensions[result]

Out[277]= {16, 16}

In[278]:= MLRemoveAll[]

In[279]:= MLCacheInfo[]

Out[279]= {}

In[280]:= MLresult = MLCache[MLListConvolve[mlkrn, mlimg, krncent, BOUNDARYCYCLIC, CONVOLVEDIRECT]]

        MathVisionCpp::mlcacheerror : Mathlink cache error.

Out[280]= MLInvalidArgumentNumber[1]
```

Data transfer (`img` and `krn` where initialized previously)

Typing error

error information

No data transfer at all

empty cache

error due to empty cache

Taking Advantage of Caching

- Using a large data set in multiple ML-function calls

```
mldata = MLCache[data];
result1 = MLFunction1[mldata];
result2 = MLFunction2[mldata];
result3 = MLFunction3[mldata]; …
```

- Using the result of a ML-function in a subsequent ML-function call

```
mlresult1 = MLFunction1[data]//MLCache;
mlresult2 = MLFunction2[mlresult1]//MLCache;
finalresult = MLFunction3[mlresult2];
```

MathLinkIO Class in C++

C++ interface to handle Mathlink communication, featuring

- `Get(…)` and `Return(…)` functions for many different standard data types + data types defined in the MathVisionC++ library. These functions transparently handle *caching* and *data type conversion*
- *Error handling*: in case of mathlink errors supplied in ML-function call, an `MLErrorType` object is `thrown`; `catch` block sends an error message to Mathematica
- In case of *wrong argument types* (e.g. wrong dimensionality of list), we use the *same error handling* scheme. This is far *more user-friendly* then using Mathematica pattern-testing on the arguments (we get an error message in Mathematica instead of undesired continuation of symbolic calculations)

Coding Example with MathLinkIO

We developed `mprepprep`, a small tool that automatically generates `mprep` files from our C++ code

```
// squareimage.cpp
#include <mathvisioncpp/datatypes/multiarray.hpp>
#include <mathvisioncpp/inputoutput/mathlink_io/mathlink_io.hpp>

using namespace MathVisionCpp;

/* MPREP
:Mathematica: MLSquareImage[image_]
*/
void MLSquareImage()
{
  IO::MathLinkIO mma;
  try {
    DataTypes::MultiArray<double,2> image;
    mma.Get(image, true); // "true" is to indicate for in-place-processing
    image *= image;
    mma.Return(image);
  }
  catch (IO::MLErrorType& i)
  { mma.Abort(i); }
}
```

Automatically generated mprep file

```
:Begin:
:Function:        MLSquareImage
:Pattern:         MLSquareImage[image_]
:Arguments:       {image}
:ArgumentTypes:   {Manual}
:ReturnType:      Manual
:End:
```

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Considerations on MathVisionC++

- Support Any-D data processing (not only 1-2-3-D)
- Efficiency and code reusability
- Small effort on user interfaces (only command-line + mathematica interface)
- Should provide alternative to Mathematica for the *larger, more complex* algorithms and experiments
- Students with a bit of C/C++ experience should be able to write their code within the library framework
- Platform independent

Most Important Algorithms

Any-D

- FIR filters, i.e. ListConvolve + ListCorrelate (spatial+Fourier); data types and convolution algebra are template parameters
- Separable FIR filters
- Inner-product taker
- Fourier tranform (i.e., wrappers to FFTW functions)
- Gaussian derivative (Jet) and GD (Jet) At
- Unser's spline interpolation

Specific-D

- Scale space interest points
- Non-linear diffusion
- Orientation scores (OS)
  - Orientation score transformation
  - G-convolutions (steerable + non-steerable)
  - OS Gaussian derivative Jet
  - OS non-linear diffusion scheme

Library Structure

Directory + namespace (first level only) structure:

```
├──basics
├──datatypes
├──listfunctions
├──inputoutput
│   ├──mathlink_io
│   └──file_io
├──interpolation
├──convolve
├──specialfunctions
├──solvers
├──transforms
├──reconstruction
├──morphology
├──scalespace
│   ├──nonlineardiffusion
│   ├──interestpoints
│   └──gaussianderivatives
├──orientationscores
│   ├──ostransforms
│   ├──osmorphology
│   ├──osdiffusion
│   ├──osderivatives
│   └──gconvolve
├──heisenbergscores
│   ├──heisenbergdiffusion
│   └──heisenbergtransforms
└──orientationscores3d
```

Library Dependencies

- Dependencies on other libraries:
  - *Boost*
  - *FFTW*
  - *MathLink*
- Work in progress: using *BLAS/LAPACK* to increase speed
- Furthermore we use
  - *Cmake* cross-platform build environment
  - *Doxygen* for documentation and tutorials
  - *SVN* for version control

Core datatypes: Vect and MultiArray

- `MultiArray<T, Rank>` is a `Rank`-dimensional datatype with elements of type `T`. For example

```
MultiArray<double, 3> foo;
MultiArray<Matrix<float,2,2>, 2> bar;
```

  - cf. *Packed Array* in Mathematica.
  - Provides “auto-allocation”, operators (e.g. *=, += etc), sub-array iterators etcetera.

- `Vect<T, Len>` is a `Len`-dimensional vector of type `T`.

```
Vect<int,3> myIntVec;
Vect<double,2> myDoubleVec;
```

- `Rank` of `MultiArray` and `Len` of `Vect` are template parameters, so values are known during compilation → Allows for more optimization by compiler.

Mathematica-inspired functions

- Mathematica-like operations in vectors, e.g.

```
Append(myIntVec, 10), Prepend(myIntVec, 10)
Take<0,2>(myIntVec), Join(myIntVec, myOtherIntVec)
```

- Mathematica-like operations on MultiArray, e.g.

```
Map_<0>(_1 > thresholdValue, thresholdedImage, niceImage);
```

Level-spec

"Pure" function (boost lambda expression)

Output

input

Compare:

```
thresholdedImage =
   Map[If[#1>thresholdvalue,1,0]&, niceImage, {2}];
```

(Note: "level-spec" convention is other way around)

- Also implemented *parallel* versions (e.g. ParallelMap)

Algorithm Interfaces

- *Class interface*: why? minimize algorithm-setup redundancy.
  Constructor – Calculate – Destructor.
  Example:

```
{
  GaussianDerivativeJet<T,Rank> MyGD(scale,
    maxDerivativeOrder, imageDimensions,
    boundaryConditions, convolutionMethod);
  MyGD.Calculate(result1, input1, 1);
  MyGD.Calculate(result2, input2, 1);
} // C++ will now call MyGD's destructor
```

- *Function interface:* provides kind of shortcut to most important algorithms. Example:

```
ListConvolve(result, image, kernel,
    kernelCenter, boundaryCondition, convolutionMethod);
```

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Examples

- All examples were run on the **bigmath2** machine:
  - 4 Dualcore Opteron 2.2Ghz CPUs
  - 64GB of ram
  - Linux
  - Mathematica 6.02
  - Gcc version 4.1.2
- The examples will demonstrate:
  - Speed difference between MathVisionC++ and Mathematica / MathVisionTools
  - Benefits of using Mathlink caching

Example: Interpolation

1. Mathematica:

```
imgintMma = ListInterpolation[img, InterpolationOrder->1]
results = imgintMma@@@{{x1,y1},{x2,y2}}
```

2. MathVisionC++ via Mathlink Interface:

```
imgintCpp = MLNewBSplineInterpolator[mlimg,1,MLBOUNDARYREFLECTIVE]
results = MLBSplineInterpolatedValue[imgintCpp,{{x1,y1},{x2,y2}}]
```

Timing result in seconds on bigmath2, single-threaded, 512 x 512 image, 1 000 000 interpolations, interpolation order 1		
	Total calculation time (including transfer)	Total transfer time
1. Mathematica	8.8 s	-
2. MathVisionC++	2.5 s	0.8 s

Transfer time includes transfer of image, list of requested interpolation coordinates and interpolation results (B-Spline coefficients are automatically *cached*; no need to transfer)

Example: GaussianDerivativeAt

Optic flow algorithm using multiscale toppoints

- Uses toppoints in scale space of an image sequence to estimate optic flow.
- Algorithm requires many GaussianDerivativeAt on the same 3D (2D+time) image: 19 calls for each toppoint.
- GaussianDerivativeAt: input=3D image, output = scalar value.

Timing results in seconds on bigmath2, single-threaded,
Yosemite sequence (316 pixels x 251 pixels x 15 frames), 819 Toppoints,
819x19 = 15561 x GaussianDerivativeAt

	Time per derivative	Total time (with transfer)	Total transfer time
Mathematica (MathVisionTools)	0.048 s	235 s	-
MathVisionC++ without any caching	0.4 s	6224 s	6212 s
MathVisionC++ with caching	0.00079 s	12.7 s	0.4 s

Example: Gradient of a 3D Image

Mathematica:

```
tx = 20.; ty = 10.; tz = 16.;
SetOptions[GaussianDerivative, Method → Convolve];
Timing[
 gradient = {GaussianDerivative[{tx, 1}, {ty, 0}, {tz, 0}][img],
   GaussianDerivative[{tx, 0}, {ty, 1}, {tz, 0}][img],
   GaussianDerivative[{tx, 0}, {ty, 0}, {tz, 1}][img]};
 gradmag = √(#1^2 + #2^2 + #3^2) & @@gradient;
]
```

Timing results on bigmath2, image size 171x100x195, all single-threaded		
	Method = Convolve	Method = Fourier
Mathematica	13, 6 s	34,1 s
C++ (gcc4)	2,9 s	3,3 s

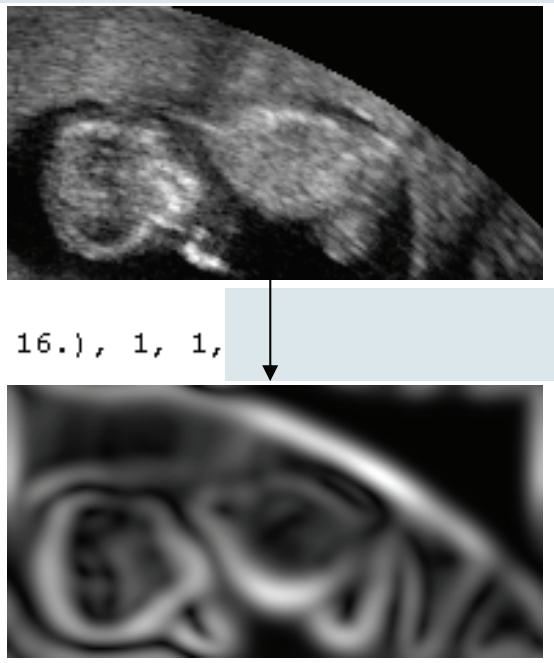
MathVisionC++ (Full C++, no Mathlink in this example):

```
_StartTiming();

MultiArray<double, 4> gradient;
CalculateGaussianDerivativeJet(gradient, img, Vect3(20., 10., 16.), 1, 1,
  BoundaryConditionVector<3>(Cyclic), ConvDirect);

MultiArray<double, 3> gradmag;
Map_<1>(Norm<2>(), gradmag, gradient);

_StopTiming();
```



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Conclusion

- Proposed a Mathlink *caching* scheme to limit the amount of Mathematica ↔ C++ data transfers
- Introduced MathVisionCpp: a C++ library for image processing
- Difference from other C(++) libraries: *Any-D* && more *mathematically-oriented* functions.
- Provide a full interface to Mathematica, to take advantage of strengths of both Mathematica and C++
- Our C++ implementations prove to be faster
- Caching mechanism allows for a large Mathlink transfer overhead reduction
- Under development, but already a lot of functionality

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