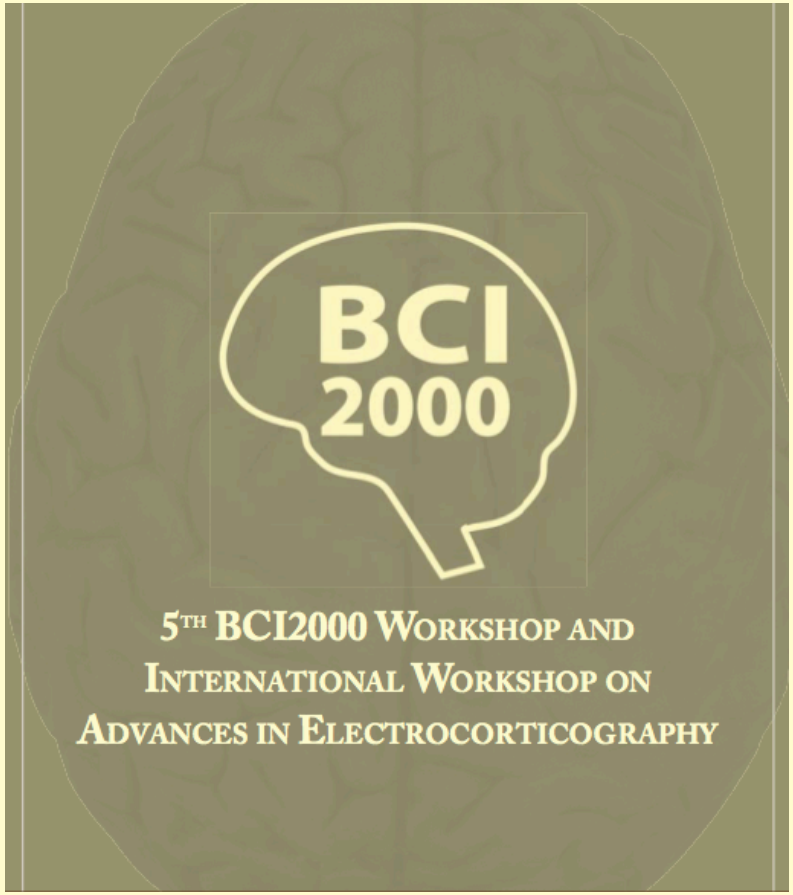
Implementing a Signal Processing Filter in BCI2000 using C++



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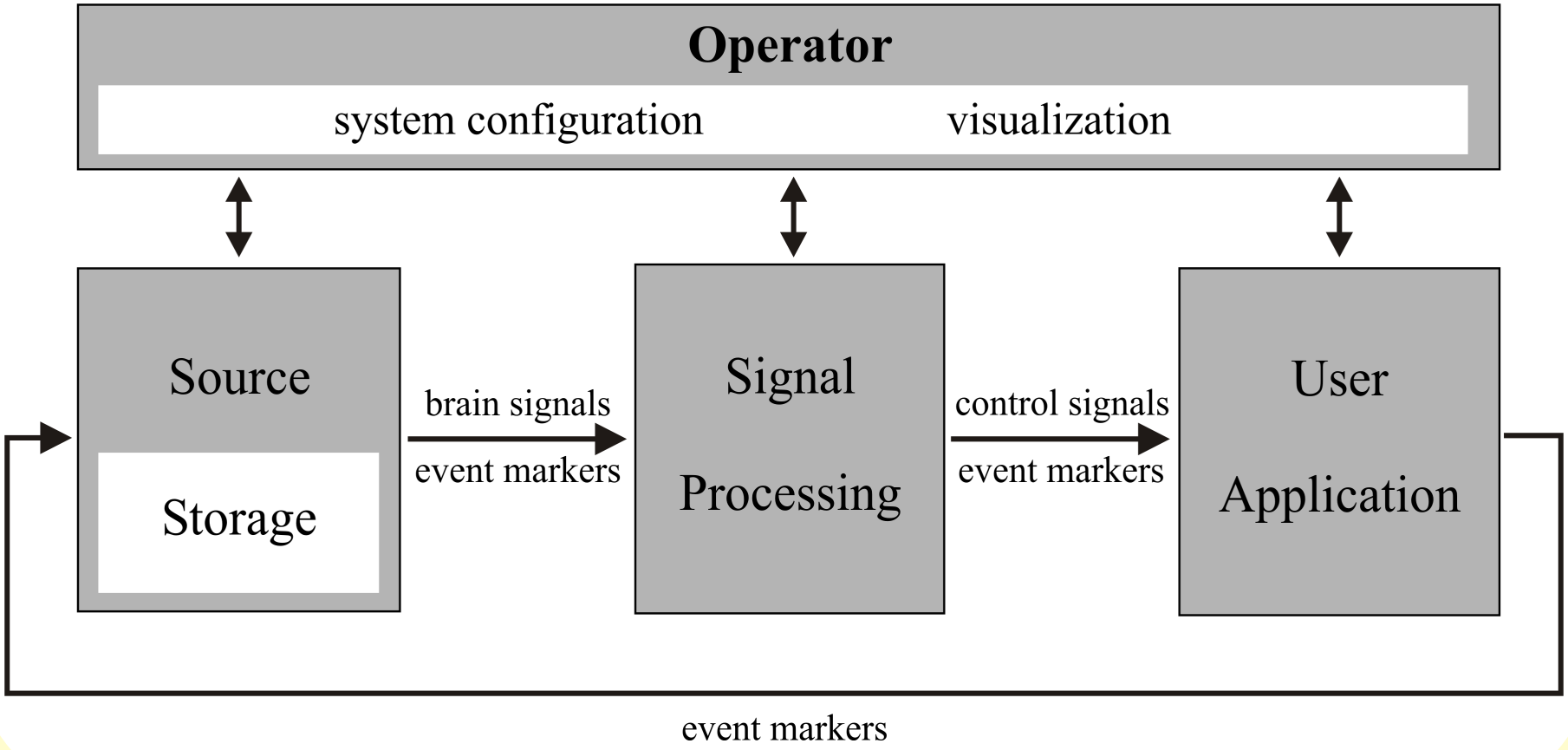
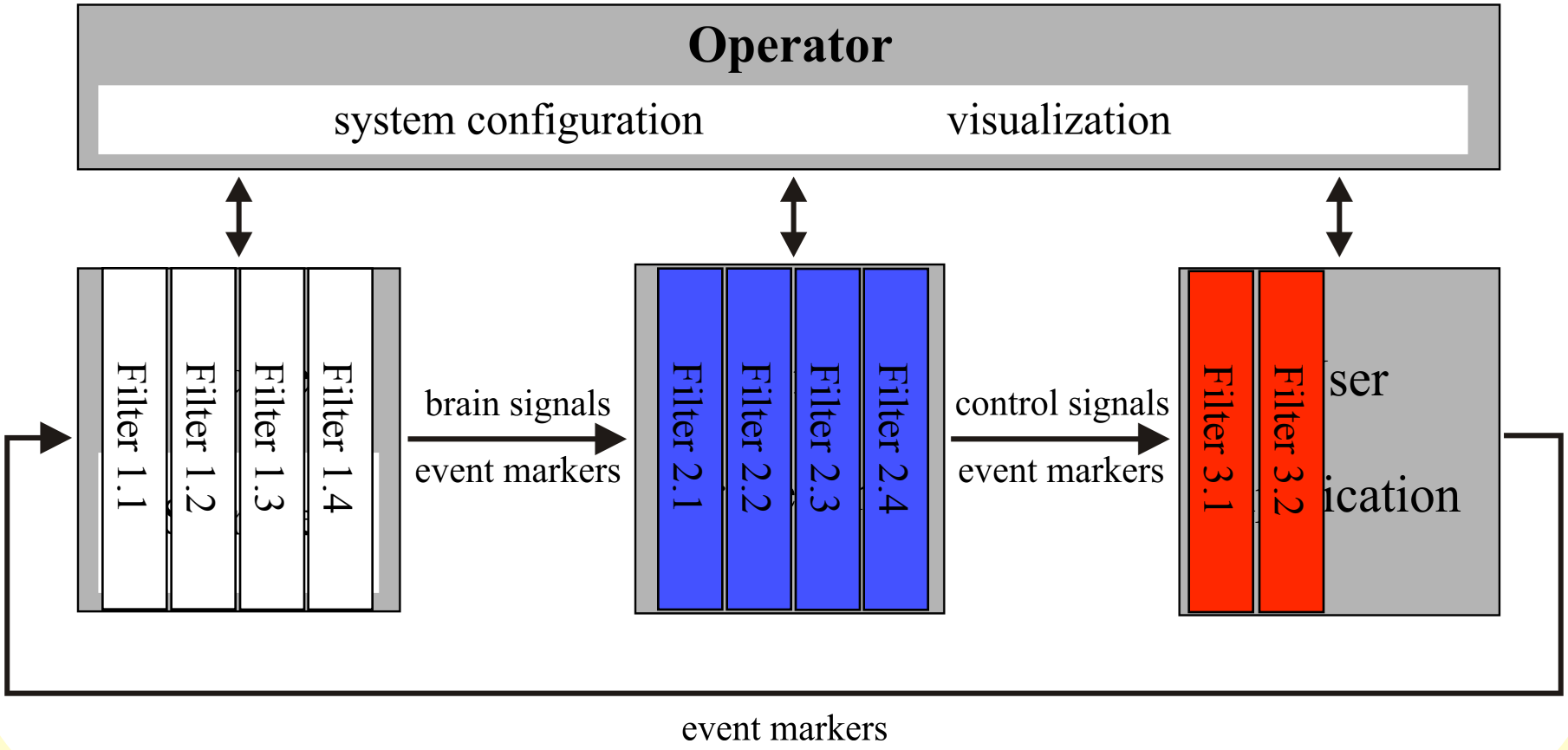
presented by

Jeremy Hill
Max Planck Institute for Biological Cybernetics
Tübingen, Germany

BCI2000 System Model

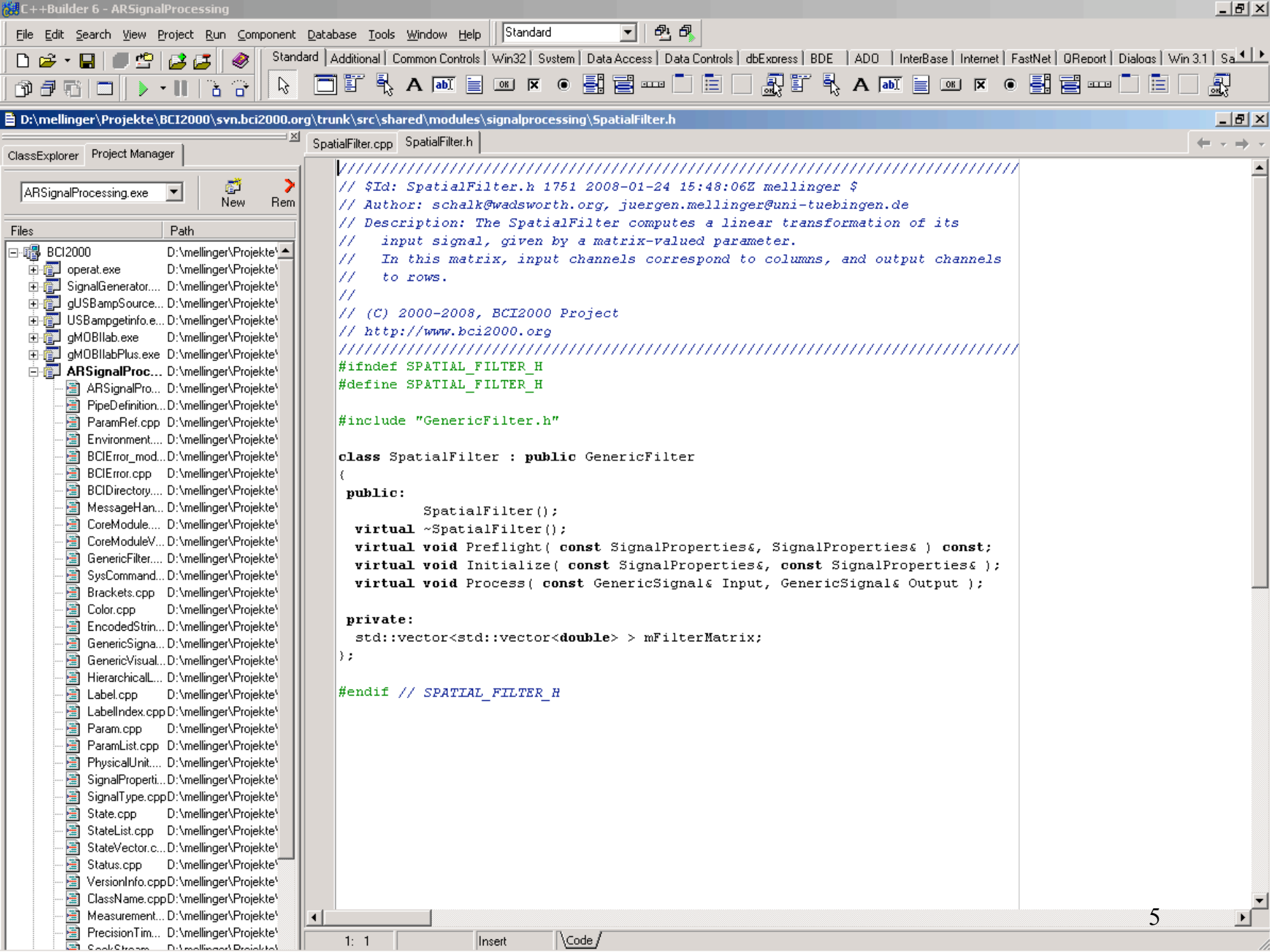


BCI2000 System Model



BCI2000 Code Base

- Written in C++
- Extensive use of STL
- Dependencies
  - Borland VCL GUI library (but soon: Qt-based)
  - Win32 API
  - Borland C++ Builder Compiler required for complete build
- Parts (mex files, command line filters, many source files) may be built using gcc


C++Builder 6 - ARSignalProcessing
File Edit Search View Project Run Component Database Tools Window Help
Standard
Standard Additional Common Controls Win32 System Data Access Data Controls dbExpress BDE ADO InterBase Internet FastNet QReport Dialogs Win 3.1
D:\mellinger\Projekte\BCI2000\svn.bci2000.org\trunk\src\shared\modules\signalprocessing\SpatialFilter.h
ClassExplorer
Project Manager
ARSignalProcessing.exe
New
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Files
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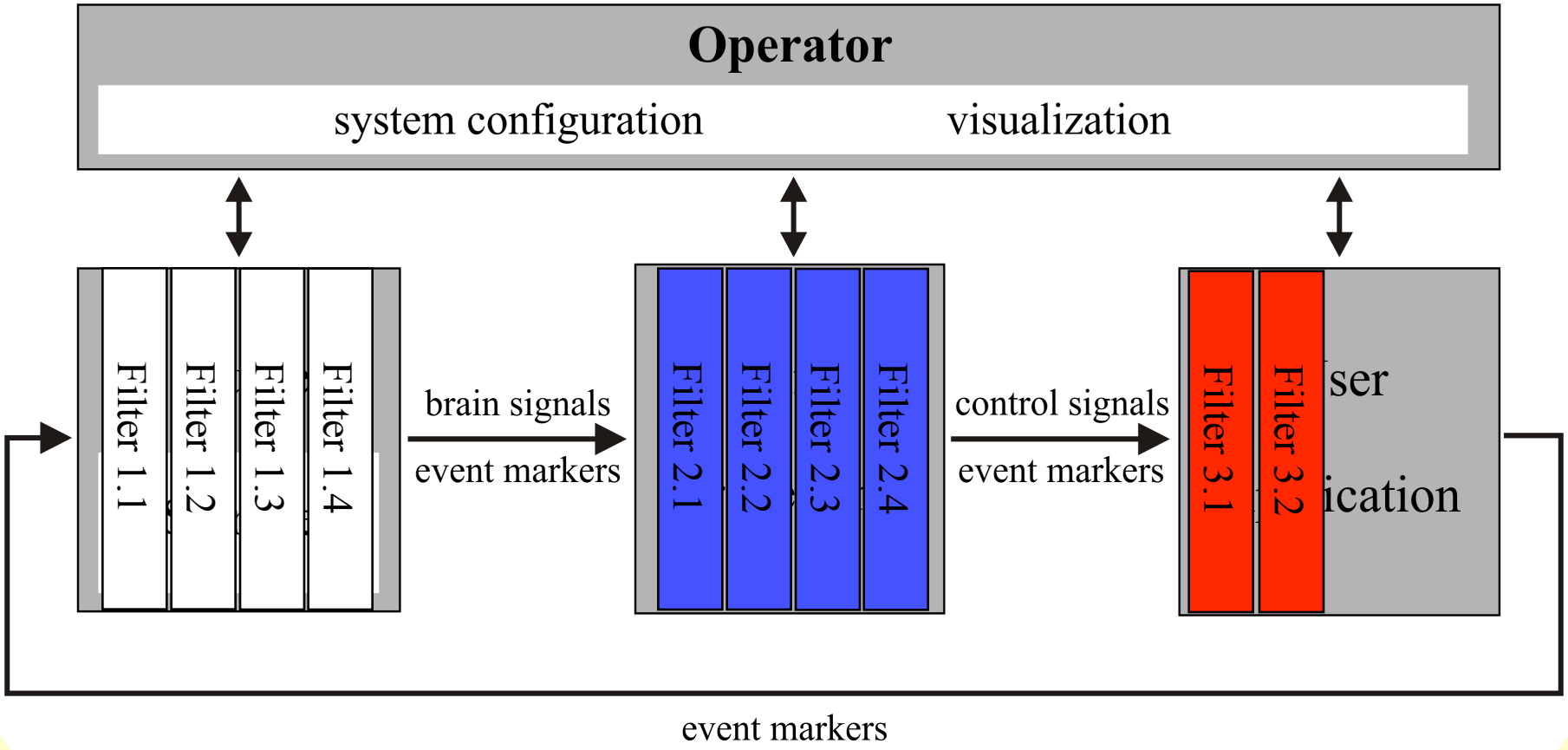
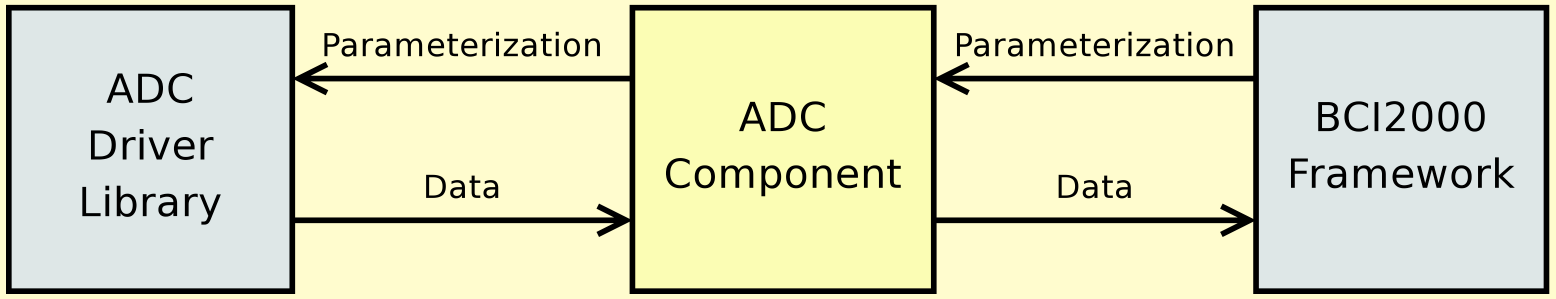
BCI2000 D:\mellinger\Projekte\
operat.exe D:\mellinger\Projekte\
SignalGenerator.... D:\mellinger\Projekte\
gUSBampSource... D:\mellinger\Projekte\
USBampgetinfo.e... D:\mellinger\Projekte\
gMOBIlab.exe D:\mellinger\Projekte\
gMOBIlabPlus.exe D:\mellinger\Projekte\
ARSignalProc... D:\mellinger\Projekte\
ARSignalPro... D:\mellinger\Projekte\
PipeDefinition... D:\mellinger\Projekte\
ParamRef.cpp D:\mellinger\Projekte\
Environment.... D:\mellinger\Projekte\
BCIError_mod... D:\mellinger\Projekte\
BCIError.cpp D:\mellinger\Projekte\
BCIDirectory.... D:\mellinger\Projekte\
MessageHan... D:\mellinger\Projekte\
CoreModule.... D:\mellinger\Projekte\
CoreModuleV... D:\mellinger\Projekte\
GenericFilter.... D:\mellinger\Projekte\
SysCommand... D:\mellinger\Projekte\
Brackets.cpp D:\mellinger\Projekte\
Color.cpp D:\mellinger\Projekte\
EncodedStrin... D:\mellinger\Projekte\
GenericSigna... D:\mellinger\Projekte\
GenericVisual... D:\mellinger\Projekte\
HierarchicalL... D:\mellinger\Projekte\
Label.cpp D:\mellinger\Projekte\
LabelIndex.cpp D:\mellinger\Projekte\
Param.cpp D:\mellinger\Projekte\
ParamList.cpp D:\mellinger\Projekte\
PhysicalUnit.... D:\mellinger\Projekte\
SignalProperti... D:\mellinger\Projekte\
SignalType.cpp D:\mellinger\Projekte\
State.cpp D:\mellinger\Projekte\
StateList.cpp D:\mellinger\Projekte\
StateVector.c... D:\mellinger\Projekte\
Status.cpp D:\mellinger\Projekte\
VersionInfo.cpp D:\mellinger\Projekte\
ClassName.cpp D:\mellinger\Projekte\
Measurement... D:\mellinger\Projekte\
PrecisionTim... D:\mellinger\Projekte\
SpatialFilter.cpp
SpatialFilter.h
//
// $Id: SpatialFilter.h 1751 2008-01-24 15:48:06Z mellinger $
// Author: schalk@wadsworth.org, juergen.mellinger@uni-tuebingen.de
// Description: The SpatialFilter computes a linear transformation of its
//   input signal, given by a matrix-valued parameter.
//   In this matrix, input channels correspond to columns, and output channels
//   to rows.
//
// (C) 2000-2008, BCI2000 Project
// http://www.bci2000.org
//
#ifndef SPATIAL_FILTER_H
#define SPATIAL_FILTER_H
#include "GenericFilter.h"
class SpatialFilter : public GenericFilter
{
 public:
          SpatialFilter();
  virtual ~SpatialFilter();
  virtual void Preflight(const SignalProperties&, SignalProperties&) const;
  virtual void Initialize(const SignalProperties&, const SignalProperties&);
  virtual void Process(const GenericSignal& Input, GenericSignal& Output);
 private:
  std::vector<std::vector<double> > mFilterMatrix;
};
#endif // SPATIAL_FILTER_H
1: 1
Insert
Code
5

BCI2000 System Model



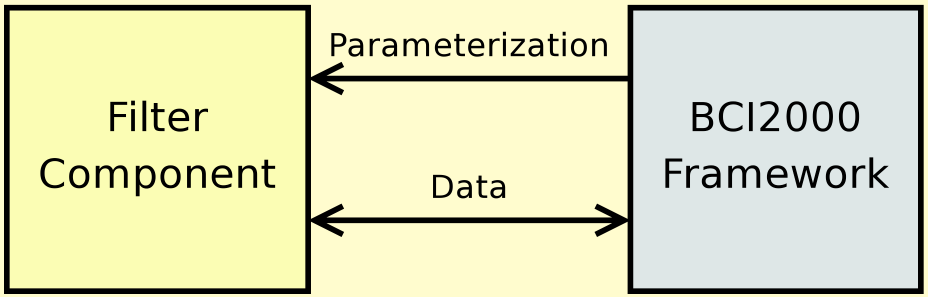
BCI2000 Source Module



Inheritance:

```
Environment                 (Parameter, State)
    GenericFilter           (Initialize, StartRun, Process, ...)
        GenericADC
            MyHardwareADC
```

BCI2000 Signal Processing



Inheritance:

```
Environment                 (Parameter, State)
    GenericFilter           (Initialize, StartRun, Process, ...)
        MyFilter
```

`GenericFilter` Class Interface

- **`GenericFilter`** defines an interface
  - implemented by your code
  - called from the BCI2000 framework
- Interface elements are event handlers
  - Initialization
  - Processing
  - Helpers
- **`C++:`** virtual functions

`GenericFilter` Class Interface

- Blockwise data processing: **`Process()`**
- Helper functions

  Constructor

  `Preflight()`

  `Initialize()`
- A few others

`GenericFilter::Process()`

- A filter's main function
- Called once for each block of data
- Single chain of filters:

  input received from preceding filter

  output fed into subsequent filter
- Filters not modifying their signal must do `Output=Input;`

`GenericFilter::Initialize()`

- Called when parameter settings have changed
- Adapt your filter's member variables to reflect new parameter settings
- No need to check for configuration errors

`GenericFilter::Preflight()`

- Called when parameter settings need verification
- Prevent configuration errors
  - report an error if settings will lead to a crash
  - report a warning if parameters appear inconsistent

`GenericFilter::StartRun()`

- Called when a new run starts – user clicks "Start" or "Resume"
- Typical **`StartRun()`** examples
  - writing a run number into a log file
  - opening a new output file
- Any initialization should *either* fit into **`Initialize()`** *or* into **`StartRun()`**

`GenericFilter::StopRun()`

- Called when a run ends
- Only place where parameter values may be modified
- Modified parameter values will be propagated to operator and other modules automatically

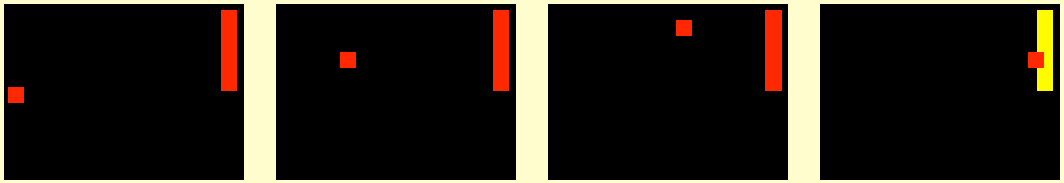
Classification

- Generally:
  - Example to category
  - Continuous (data) to discrete (label)
- Classification function:
  - Multi-dimensional continuous data $\vec{x}$
  - Continuous 1D classification function $f(\vec{x})$
  - Discretization $\Theta(f(\vec{x}) - \alpha)$
- Linear classification $f(\vec{x}) = \sum_i x_i w_i$
- Training algorithms

  LDA, linear SVM, Perceptron

BCI Classification

Continuous feedback:



$$\textit{brain state} \mapsto \textit{cursor} \mapsto \textit{target/class}$$

$$\vec{x} \qquad f(\vec{x})$$

Data Acq Sig Proc Application

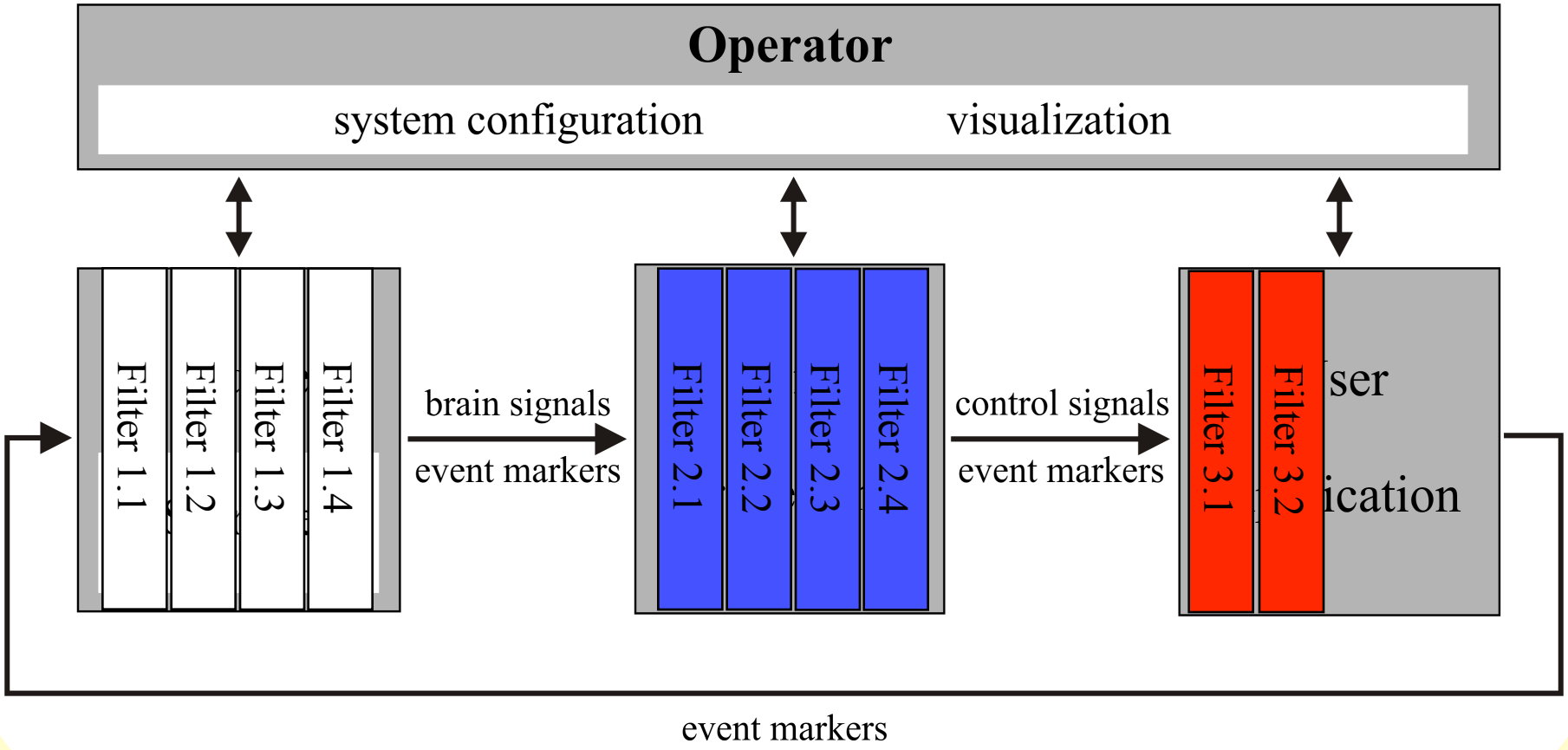
Tutorial Example: Linear Classifier

- Linear classification function
- Sparse representation: nonzero weights only
- Multiple output channels

$$f(x) = \sum_{kl} w_{kl}\, x_{kl}$$

$$f_j(x) = \sum_{kl} w_{jkl}\, x_{kl}$$

BCI2000 System Model



Tutorial Example: Linear Classifier

- Derive a new class **`LinClassifier`** from **`GenericFilter`**
- Implement its **`Process()`**, **`Initialize()`**, **`Preflight()`**, and constructor functions
- Add it to the filter chain

Declaring a **`LinClassifier`** Class

Contents of **`LinClassifier.h`**:

```
#ifndef LIN_CLASSIFIER_H
#define LIN_CLASSIFIER_H

#include "GenericFilter.h"

class LinClassifier : public GenericFilter
{
 public:
   LinClassifier();
   ~LinClassifier();

   void Preflight( const SignalProperties&, SignalProperties& ) const;
   void Initialize( const SignalProperties&, const SignalProperties& );
   void Process( const GenericSignal&, GenericSignal& );
};
#endif // LIN_CLASSIFIER_H
```

LinClassifier::Process()

```
void LinClassifier::Process( const GenericSignal& Input,
                                   GenericSignal& Output )
{
  for( int ch = 0; ch < Output.Channels(); ++ch )
    for( int el = 0; el < Output.Elements(); ++el )
      Output( ch, el ) = 0.0;

  for( size_t i = 0; i < mWeights.size(); ++i )
    Output( mOutputChannels[ i ], 0 )
     += Input( mInputChannels[ i ], mInputElements[ i ] )
        * mWeights[ i ];
}
```

$$f_j(x) = \sum_{kl} w_{jkl}\, x_{kl}$$

Data Members

```
#include <vector>
...
class LinClassifier : public GenericFilter
{
 public:
  ...
 private:
  std::vector<float> mOutputChannels,
                     mInputChannels,
                     mInputElements,
                     mWeights;
};
```

$$f_j(x) = \sum_{kl} w_{jkl}\, x_{kl}$$

LinClassifier::Initialize()

```
void LinClassifier::Initialize( const SignalProperties& Input,
                                const SignalProperties& Output )
{
  const ParamRef& Classifier = Parameter( "Classifier" );
  size_t numEntries = Classifier->NumRows();
  mInputChannels.resize( numEntries );
  ...
  for( size_t entry = 0; entry < numEntries; ++entry
  {
    mInputChannels[ entry ] = Classifier( entry, 0 ) - 1;
    mInputElements[ entry ] = Classifier( entry, 1 ) - 1;
    mOutputChannels[ entry ] = Classifier( entry, 2 ) - 1;
    mWeights[ entry ] = Classifier( entry, 3 );
  }
}
```

`LinClassifier::Preflight()`

Potential errors:

- inappropriate dimensions of *Classifier* matrix parameter
- index out of range in input
- index out of range in output

LinClassifier::Preflight()

```
void
LinClassifier::Preflight( const SignalProperties& Input,
                                SignalProperties& Output) const
{ // Check matrix format
  if( Parameter( "Classifier" )->NumColumns() != 4 )
    bcierr << "Classifier parameter must have 4 columns "
           << "(input channel, input element, "
           << "output channel, weight)"
           << endl;

  // Check indices and obtain max output channel
  ...
  // Request output dimensions
  Output = SignalProperties( maxChannel, 1 );
}
```

LinClassifier::LinClassifier()

```
LinClassifier::LinClassifier()
{
 BEGIN_PARAMETER_DEFINITIONS
  "Filtering matrix Classifier= 2 "
  "[ input%20channel input%20element%20(bin) output%20channel weight ] "
  "              1                          4                 1      1   "
  "              1                          6                 2      1   "
  " % % % // Linear classification matrix in sparse representation",
  END_PARAMETER_DEFINITIONS
}
```

Compiling **LinClassifier.cpp**

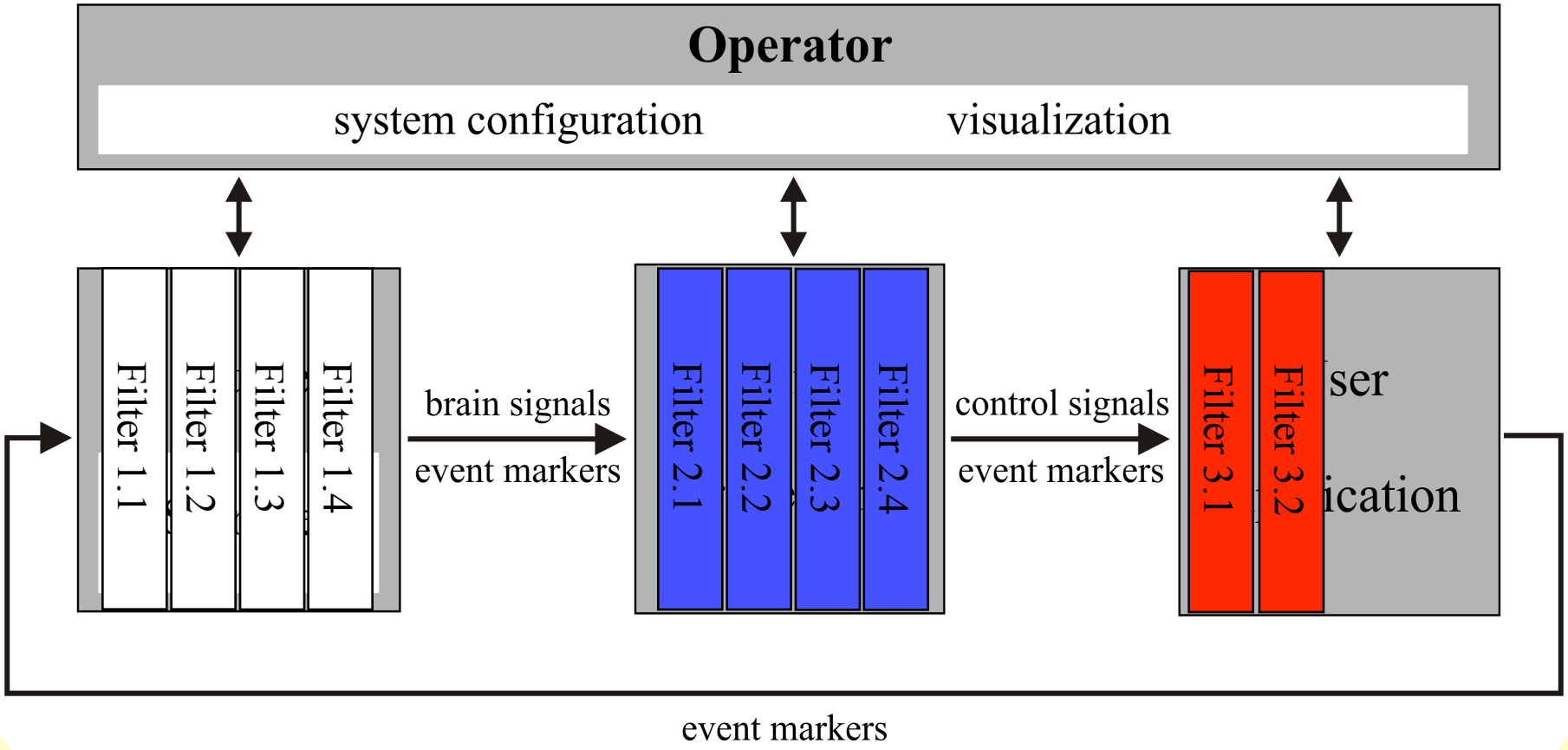
```
#include "PCHIncludes.h" // Make the compiler's Pre-Compiled
#pragma hdrstop          // Headers feature happy

#include "LinClassifier.h"
#include "BCIError.h"
#include <algorithm> // for std::max()

using namespace std;

...
```

BCI2000 System Model



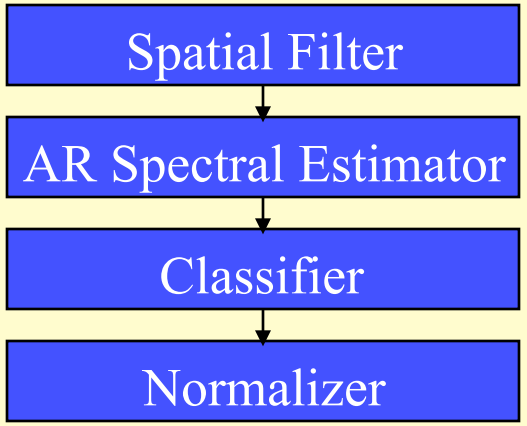
Instantiating `LinClassifier` in a Signal Processing module

PipeDefinition.cpp:

```
...
#include "LinClassifier.h";
...

Filter( SpatialFilter, 2.A );
Filter( ARFilter, 2.B );
Filter( LinClassifier, 2.C );
Filter( NormalFilter, 2.D );
```

Filter chain:



Framework Recapitulation

- Parameter access
- State access
- Reporting errors and warnings

Parameter Access

- Getting parameter values:

```
float myFloat = Parameter( "SamplingRate" );
```

- Setting parameter values:

```
Parameter( "TimeConstant" ) = myFloat;
```

- Matrix parameters:

```
myFloat = Parameter( "MUD" )( 0, 2 );
myFloat = Parameter( "Audio" )( "Task", 2 );
myFloat = OptionalParameter( "MUD", 1 )( 20, 30 );
```

State Access

- Getting state values:

```
short targetCode = State( "TargetCode" );
```

- Setting state values:

```
State( "ResultCode" ) = targetHit;
```

- Optional states:

```
short artifact = OptionalState( "Artifact", 0 );
```

- Per-sample access:

```
State( "Artifact" )( 3 ) = 1;
```

Reporting Errors and Warnings

```
using namespace std;
```

- C++ command-line programs use

```
cout << "The result is " << result << "." << endl;
cerr << "This is an error message." << endl;
```

- BCI2000 filters use

```
bciout << "The result is " << result << "." << endl;
bcierr << "TimeConstant must be greater 0." << endl;
```

- Side effects

`endl` is `'\n'` forcing immediate display

`bcierr` from `Preflight()`: Prevents `Initialize()`

`bcierr` elsewhere: Terminates module

Signal Units and Labels

- Consistent choice of visualization scale
- Visualization in correct units
- User convenience
  - classifier configuration in terms of frequencies (SMR) or temporal offsets (ERP)
  - hardware-independence
- Automatic conversion

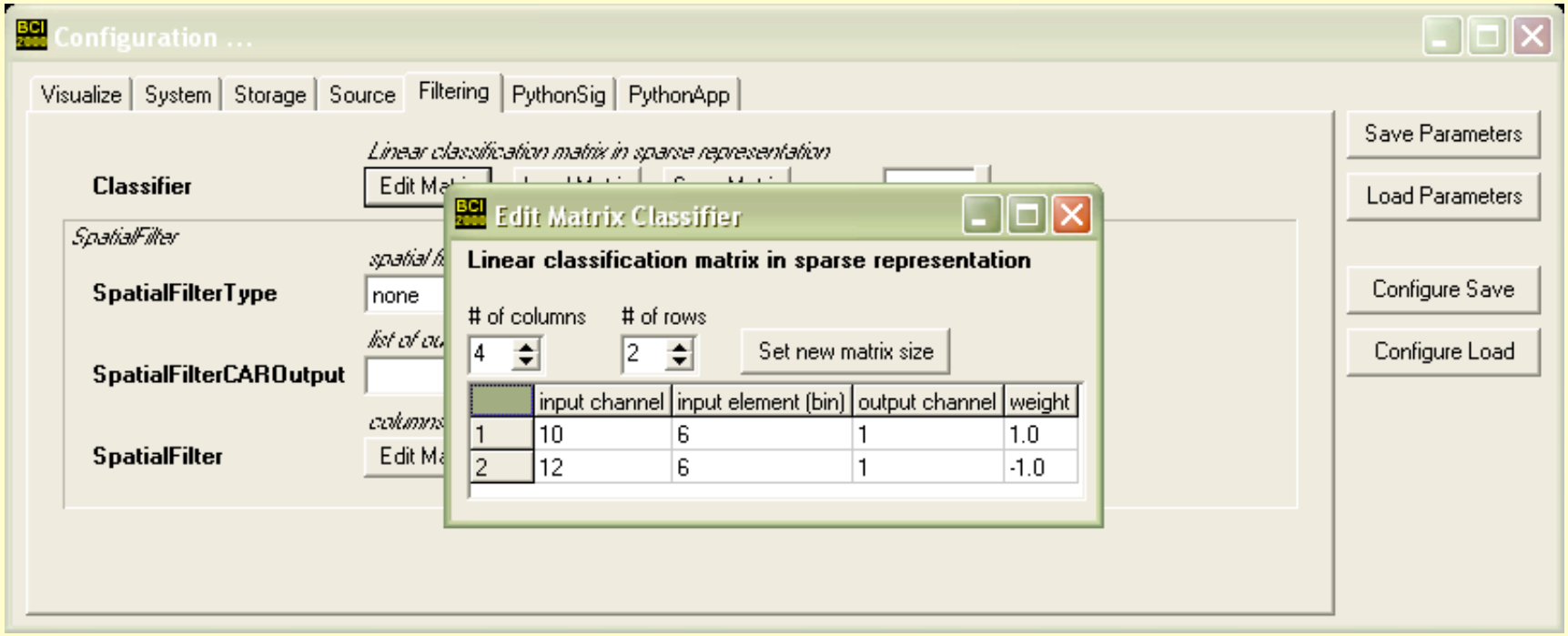
```
channel = Signal.ChannelIndex("Cz");
element = Signal.ElementIndex("25Hz");
```

Signal Units and Labels

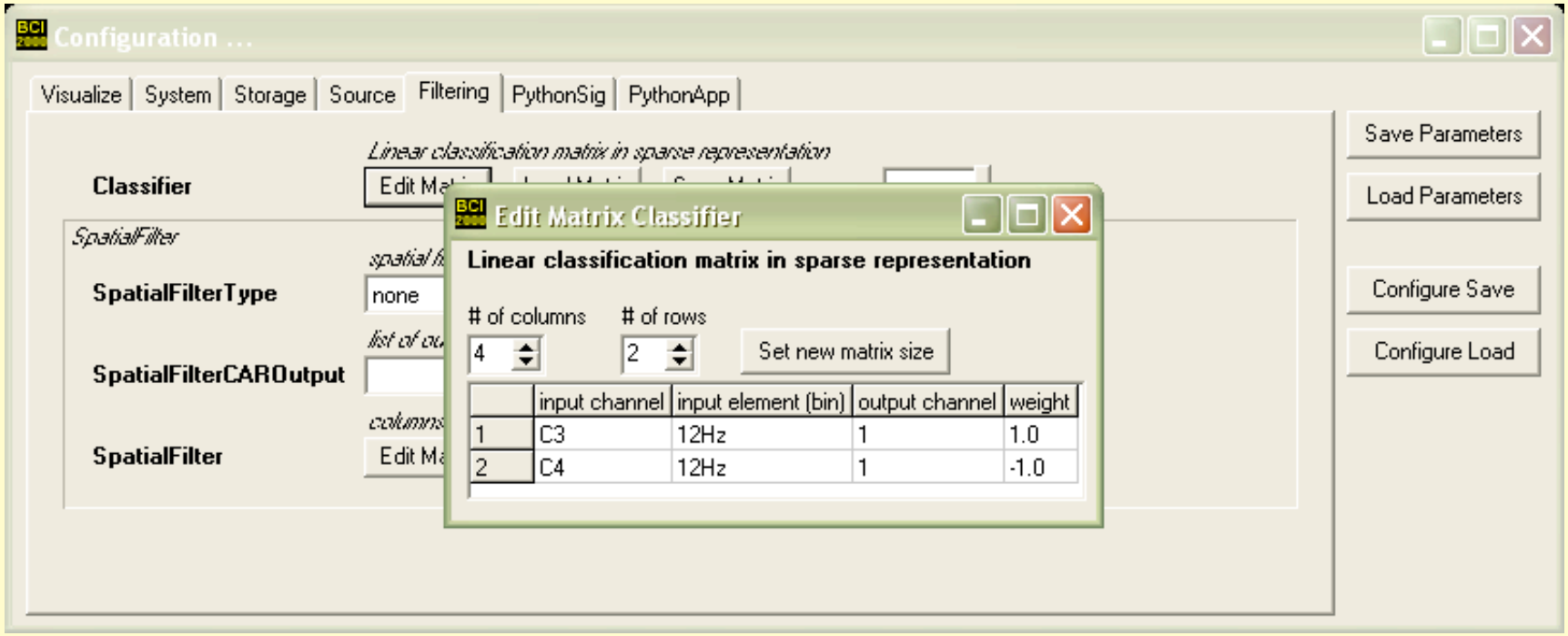
User-friendly index specification:

```
void LinClassifier::Initialize( const SignalProperties& Input,
                                const SignalProperties& Output )
{
  const ParamRef& Classifier = Parameter( "Classifier" );
  ...
  for( size_t entry = 0; entry < numEntries; ++entry
  {
    mInputChannels[ entry ] = Input.ChannelIndex( Classifier( entry, 0 ) );
    mInputElements[ entry ] = Input.ElementIndex( Classifier( entry, 1 ) );
    ...
  }
}
```

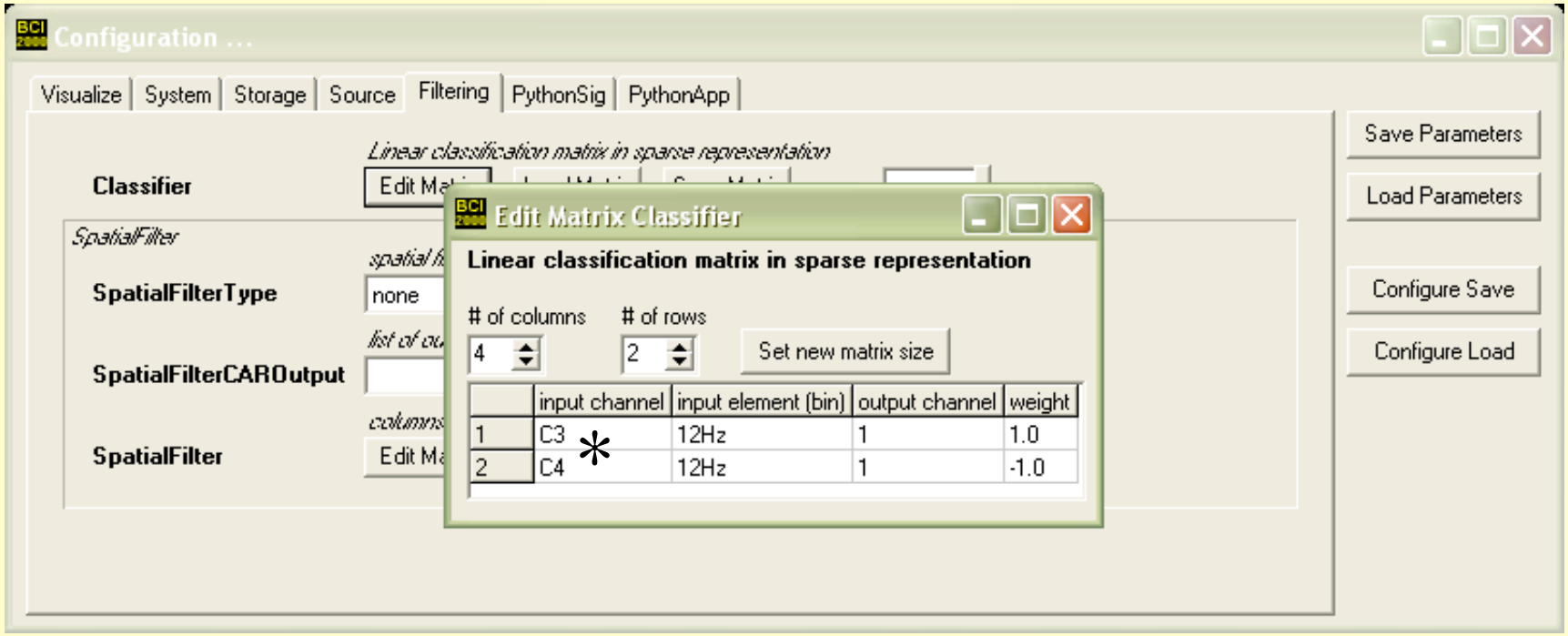
Signal Units and Labels



Signal Units and Labels

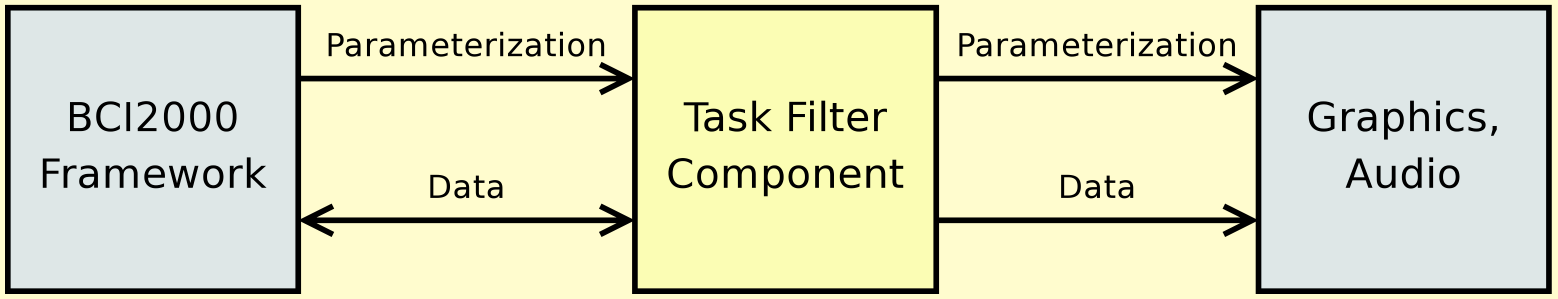


Signal Units and Labels



* "C3" and "C4", huh? If you're classifying bandpower features from *EEG,* then I hope you've done some careful spatial filtering first…

BCI2000 Application



- `GraphObject`
- Images, Text
- Audio Players
- 3D API

Conclusion

- BCI2000 is written in C++ and currently requires the Borland C++ environment.
- BCI2000 consists of four modules, each of which contains a number of filters.
- Extending BCI2000 is done by deriving your own filter class from `GenericFilter`.
- Begin with coding the core functionality into your filter's `Process()` member function, then derive other member functions.

Share your ideas, suggestions, annoyances

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