GNU Radio Internals

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Source material and Warning

- These slides were built from many sources among which:
  - Gnuradio wiki tutorial (https://wiki.gnuradio.org/index.php/Tutorials)
  - Gnuradio API doc (https://gnuradio.org/doc/doxygen/), various GNU Radio version available
  - Tom Rondeau slides (http://www.trondeau.com/)
  - "Developing Signal Processing Blocks for Software Defined Radio", Gunjan Verma and Paul Yu, Army Research Laboratory, ARL-TR-5897, 2012.
- Gnuradio is evolving quickly, some of the details mentioned here can become optional or are not yet deployed if you use older version

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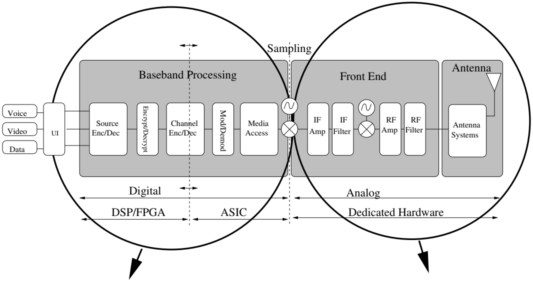
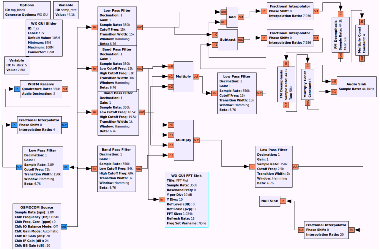
What is GNU Radio?

An open source framework for building software radio transceivers

- An open source software toolkit
  - Creating signal processing applications
  - Defining waveforms in software
  - Processing waveforms in software
- An important development community
  - Active developer community producing examples
  - GNU radio conference (2011-2014)
- A set of hardware platforms
  - USRP1 & USRP2, Universal Software Radio Peripheral,
  - RTL2832 TV tuners
- an *easy-to-use* approach (Simulink-like)

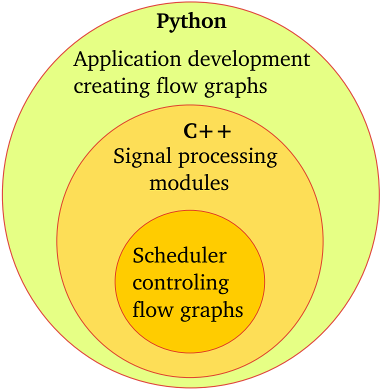
The big picture





A 3 tier architecture

- Python scripting language used for creating "‘signal flow graphs"’
- C++ used for creating signal processing blocks
  - An already existing library of signalling blocks
  - Tools for enabling the addition of new blocks
- The scheduler is using Python’s built-in module threading, to control the ‘starting’, ‘stopping’ or ‘waiting’ operations of the signal flow graph.

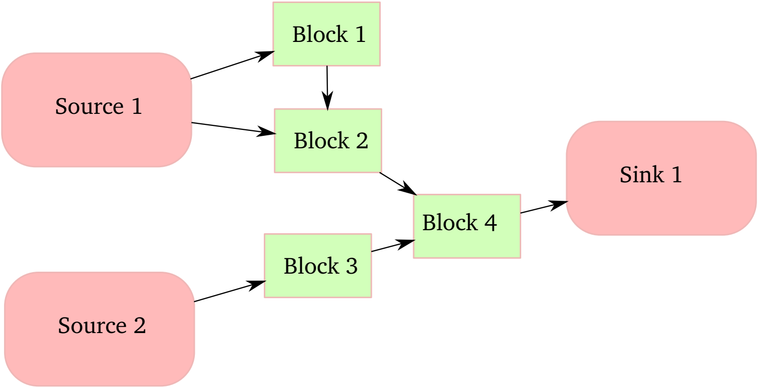


GNU Radio ‘Hello World’ application

```
#!/usr/bin/env python

from gnuradio import analog
from gnuradio import blocks
from gnuradio import audio
from gnuradio import gr

class top_block(gr.top_block):
    def __init__(self):
        gr.top_block.__init__(self, "Hello Word")

        samp_rate = 32000
        freq1=440
        ampl = 0.4

        self.audio_sink = audio.sink(32000, "", True)
        self.analog_sig_source_1 = analog.sig_source_f(samp_rate,
                    analog.GR_COS_WAVE, 350, ampl, 0)
        self.analog_sig_source_0 = analog.sig_source_f(samp_rate,
                    analog.GR_COS_WAVE, 440, ampl, 0)

        self.connect((self.analog_sig_source_0, 0), (self.audio_sink, 1))
        self.connect((self.analog_sig_source_1, 0), (self.audio_sink, 0))

if __name__ == '__main__':
    tb = top_block()
    tb.start()
    raw_input ('Press Enter to quit: ')
    tb.stop ()
```

Data-flow programming

- Sources, Sinks, Computational Blocks and Data Flows



GNU Radio Library

Fundamentals

- gr-analog
- gr-audio
- gr-blocks
- gr-channels
- gr-digital
- gr-fec
- gr-fft
- gr-filter
- gr-trellis
- gr-vocoder
- gr-wavelet

Graphical Interfaces

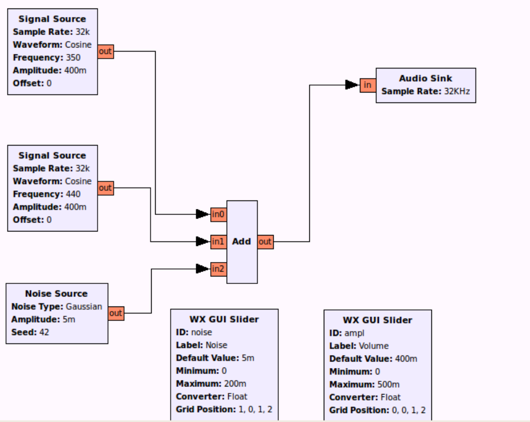
- gr-qtgui
- gr-wxgui

Hardware Interfaces

- gr-audio
- gr-comedi
- gr-shd
- gr-uhd

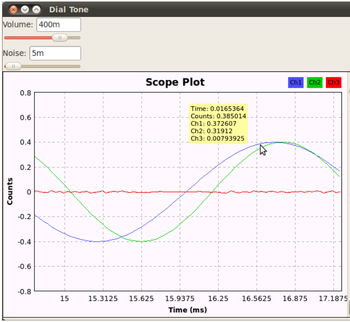
A simple example with GNU Radio companion (GRC)

- Dial tone `GNURADIO/gr-audio/example/grc/dial-tone.grc`

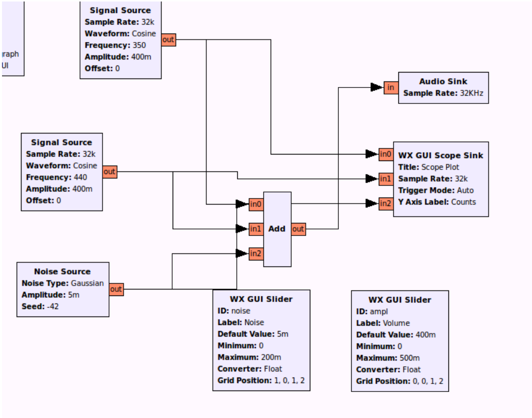


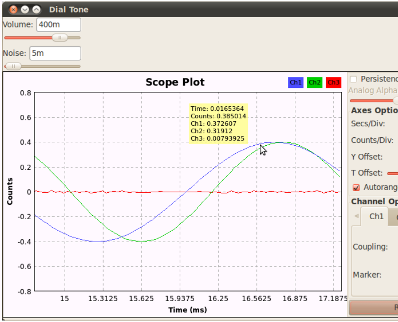
Run-Time Execution

- The `dial-tone.grc` in an XML interface instantiating python and C++ code.
- It can be:
  - Compiled (it generates a python file: `dial-tone.py`)
  - Executed (i.e. executes the generated python file)
  - Debugged (with spectrum analyzer for instance)



Debugging dial tone





Dial Tone: GRC XML code

```
<?xml version='1.0' encoding='ASCII'?>
<flow_graph>
  <timestamp>Tue May  6 17:48:23 2014</timestamp>
  <block>
    <key>options</key>
    <param>
      <key>id</key>
      <value>dial_tone</value>
    </param>
    <param>
      <key>_enabled</key>
      <value>True</value>
    </param>
    <param>
      <key>title</key>
      <value>Dial Tone</value>
    </param>
    <param>
      <key>author</key>
      <value>Example</value>
[...]
```

```
 <block>
   <key>analog_sig_source_x</key>
   <param>
     <key>id</key>
     <value>analog_sig_source_x_0</value>
   </param>
   <param>
     <key>_enabled</key>
     <value>True</value>
   </param>
   <param>
     <key>type</key>
     <value>float</value>
   </param>
   <param>
     <key>samp_rate</key>
     <value>samp_rate</value>
   </param>
   [...]
 </block>
[...]
<connection>
   <source_block_id>blocks_add_xx</source_block_i
   <sink_block_id>audio_sink</sink_block_id>
   <source_key>0</source_key>
   <sink_key>0</sink_key>
 </connection>
 <connection>
   <source_block_id>analog_sig_source_x_0</source
   <sink_block_id>blocks_add_xx</sink_block_id>
   <source_key>0</source_key>
```

Dial Tone: Python code (manual)

```
from gnuradio import gr
from gnuradio import audio
from gnuradio.eng_option import eng_option
from optparse import OptionParser
from gnuradio import analog

class my_top_block(gr.top_block):

    def __init__(self):
        gr.top_block.__init__(self)

        [....]
        sample_rate = int(options.sample_rate)
        ampl = 0.1

        src0 = analog.sig_source_f(sample_rate, analog.GR_SIN_WAVE, 350, ampl)
        src1 = analog.sig_source_f(sample_rate, analog.GR_SIN_WAVE, 440, ampl)
        dst = audio.sink(sample_rate, options.audio_output)
        self.connect(src0, (dst, 0))
        self.connect(src1, (dst, 1))

if __name__ == '__main__':
    try:
        my_top_block().run()
    except KeyboardInterrupt:
        pass
```

Dial Tone: Python code (generated from .grc)

```
#!/usr/bin/env python
##################################################
# Gnuradio Python Flow Graph
# Title: Dial Tone
# Author: Example
# Description: example flow graph
# Generated: Tue May  6 17:48:25 2014
##################################################

from gnuradio import analog
from gnuradio import audio
from gnuradio import blocks
[...]
class dial_tone(grc_wxgui.top_block_gui):

    def __init__(self):
        grc_wxgui.top_block_gui.__init__(self, title="Dial Tone")
        _icon_path = "/usr/share/icons/hicolor/32x32/apps/gnuradio-grc.png"
        self.SetIcon(wx.Icon(_icon_path, wx.BITMAP_TYPE_ANY))

        self.samp_rate = samp_rate = 32000
        self.noise = noise = .005
        self.ampl = ampl = .4

        _noise_sizer = wx.BoxSizer(wx.VERTICAL)
        self._noise_text_box = forms.text_box(
         parent=self.GetWin(),
         sizer=_noise_sizer,
         value=self.noise,
         callback=self.set_noise,
         label="Noise",
```

Dial Tone: C++ code (manual)

```
/*
 * GNU Radio C++ example creating dial tone
 * ("the simplest thing that could possibly work")
 *
 * Send a tone each to the left and right channels of stereo audio
 * output and let the user's brain sum them.
 */

#include <gnuradio/top_block.h>
#include <gnuradio/analog/sig_source_f.h>
#include <gnuradio/audio/sink.h>

using namespace gr;

int main(int argc, char **argv)
{
  int rate = 48000; // Audio card sample rate
  float ampl = 0.1; // Don't exceed 0.5 or clipping will occur

  // Construct a top block that will contain flowgraph blocks.  Alternatively,
  // one may create a derived class from top_block and hold instantiated blocks
  // as member data for later manipulation.
  top_block_sptr tb = make_top_block("dial_tone");

  // Construct a real-valued signal source for each tone, at given sample rate
  analog::sig_source_f::sptr src0 = analog::sig_source_f::make(rate, analog::GR_SIN_WAVE, 350, ampl);
  analog::sig_source_f::sptr src1 = analog::sig_source_f::make(rate, analog::GR_SIN_WAVE, 440, ampl);

  // Construct an audio sink to accept audio tones
  audio::sink::sptr sink = audio::sink::mak
```

GNU Radio software layers

- GRC: Graphical design tool
  - `GNURADIO/gr-audio/example/grc/dial-tone.grc`
  - ...
- python : Mostly Composite Block application
  - `GNURADIO/gr-audio/examples/python/dial_tone.py`
  - `GNURADIO/gr-digital/python/digital/ofdm.py`
  - ...
- C++ : Mostly Low level functions
  - `GNURADIO/gr-audio/examples/c++/dial_tone.cc`
  - `GNURADIO/gr-digital/lib/ofdm_cyclic_prefixer_impl.c`
  - ...

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GNU radio C++ naming convention

- Words in identifiers are separated by underscores (e.g. `gr_vector_int`)
- All types begin by `gr` (e.g. `gr_float`)
- All class variable begin by `d_` (e.g. `d_min_stream`)
- Each C++ class is implemented in a separated file (e.g. class `gr_magic` implemented in file `gr_magic.cc` with header file `gr_magic.h`)
- All signal processing blocs contain their input and output types in their suffixes. e.g.:

dc_blocker_ff_impl.cc

```
[..]
dc_blocker_ff_impl::
  dc_blocker_ff_impl(int D, bool long_form)
  : sync_block("dc_blocker_ff",
      io_signature::make (1, 1, sizeof(float)),
      io_signature::make (1, 1, sizeof(float))),
  d_length(D), d_long_form(long_form)
```

dc_blocker_cc_impl.cc

```
[..]
dc_blocker_cc_impl::dc_blocker_cc_impl(int D, bool long
   : sync_block("dc_blocker_cc",
       io_signature::make (1, 1, sizeof(gr_complex)),
       io_signature::make (1, 1, sizeof(gr_complex))),
    d_length(D), d_long_form(long_form)
```

Block signature

- A bloc signature is a specification of the data types that enter or exit the bloc.
- There are always two bloc signatures, one for inputs, the other for outputs.
- Each bloc signature specifies the number and types of ports.
- excerpt from `gr_io_signature.h`:

```
class GR_RUNTIME_API io_signature
{
  int                    d_min_streams;
  int                    d_max_streams;
  std::vector<int>       d_sizeof_stream_item;

  io_signature(int min_streams, int max_streams,
               const std::vector<int> &sizeof_stream_items);

public:
  typedef boost::shared_ptr<io_signature> sptr;

  ~io_signature();

  static sptr make(int min_streams, int max_streams,
                   int sizeof_stream_item);
  /*!
   * \brief Create an i/o signature
   *
```

Boost Pointer

- Gnu radio uses `Boost` smart pointers.
- `Boost` is a software library that provides a *smart* implementation of C++ pointers that offers garbage collection (i.e. delete object not used anymore).
- Gnu radio uses only the `shared_ptr` type of `Boost`
- Instead of declaring a pointer to a type `X`:

  `X* myPointer;`

  you can declare:

  `boost::shared_ptr<X> myBoostPointer`
- example in `gr_io_signature`

```
typedef boost::shared_ptr<io_signature> sptr;
static sptr make(int min_streams, int max_streams,
                 int sizeof_stream_item);
```

Volk library

- Gnu radio uses VOLK (which stands for Vector-Optimized Library of Kernels)
- `volk` provides a number of optimized function for vector processing using SIMD instructions.
- Developing with `volk` might be tricky because it is sensible to alignment of vector in memory.
- Understanding code using `volk` simply requires to understand `volk` naming convention:
  - The basic naming scheme will look something like this:
    `volk_(inputs params)_[name]_(output params)_[alignment]`
  - example:

```
volk_32f_invsqrt_32f
```

Other Volk example

- General naming convention when there are several inputs or outputs:

```
volk_(input_type_0)_x(input_num_0)_(input_type_1)_x(input_num_1)_...
    _[name]_(output_type_0)_x(output_num_0)_(output_type_1)_x(output_num_1)_..._[alignment]
```

- Examples:
  - Multiply two complex float vectors together (aligned and unaligned versions) and the dispatcher:

    ```
    volk_32fc_x2_multiply_32fc_a
    volk_32fc_x2_multiply_32fc_u
    volk_32fc_x2_multiply_32fc
    ```

  - Add four unsigned short vectors together:

    ```
    volk_16u_x4_add_16u
    ```

  - Multiply a complex float vector by a short integer:

    ```
    volk_32fc_s16i_multiply_32fc
    ```

SWIG

- SWIG is a software development tool that connects programs written in C and C++ with a variety of high-level programming languages.
- SWIG is used in GNU Radio to link Python and C++ code

SWIG example (1)

- write a C file `example.c` code that defines the `int fact(int n)` function.
- write an *interface* file for SWIG:

```
%module example
%{
  int fact(int n);
%}
int fact(int n);
```

- execute the `swig` command:
  `swig -python example.i`

⇒ it generates a file `example_wrap.c`

- Compile the .c files with -fPIC option (and path to Python.h):
  `gcc -fPIC -I/usr/include/python2.7 -c example.c example_wrap.c`

SWIG example (1)

- link it to **_example.so**:
  `ld -shared example.o example_wrap.o -o _example.so`
- import **example** in python and use the `func` function:
  python [...] `>>> import example`
  ```
  >>> example.fact(5)
  120
  ```

Creating GNU radio modules

- A gnu radio module `newModule` corresponds to a directory `newModule` should contain the following directories:
  `CMakeLists.txt docs grc include lib python swig`
- the `gr_modtool` tool helps you create the various directory
- Hence the flow for creating a block in a module
  - Create the module file hierarchy with `gr_modtool`
  - Create a block in the module with `gr_modtool`
  - Edit the C++ file to code the module functionalities
  - Test, debug and validate the functionalities

Creating a trivial module: module creation

- creating the module directory structure:
  `gr_modtool newmod arith`
- Go into the new directory:

```
$ cd gr-arith/
$ ls
apps   CMakeLists.txt  examples  include  MANIFEST.md  swig
cmake  docs            grc       lib      python
```

Creating a trivial module: adding a bloc `times2`

- We will create a bloc of type general block without parameter.
- Go into the module directory (`$ cd gr-arith/`) and type the following command:
  `gr_modtool add -t general times2`
  Answer `cpp` to the first question and **nothing** to the other questions.
- create a python test method: edit `python/qa_times2.py`
- update `python/CMakeLists.txt` (nothing to do here)
- create the build directory `cd ..;mkdir build;`
- build the project: `cd build; cmake ../`

Creating a trivial module: directory hierarchy

```
gr-arith
   [...]
|-- CMakeLists.txt
|-- docs
|    |-- CMakeLists.txt
|    |-- doxygen
|    |    |-- CMakeLists.txt
     [....]
|-- grc
|    |-- arith_times2.xml
|    `-- CMakeLists.txt
|-- include
|    `-- arith
|         |-- api.h
|         |-- CMakeLists.txt
|         `-- times2.h
|-- lib
|    |-- CMakeLists.txt
|    |-- qa_arith.cc
|    |-- qa_arith.h
|    |-- qa_times2.cc
|    |-- qa_times2.h
|    |-- test_arith.cc
|    |-- times2_impl.cc
|    |-- times2_impl.cc~
|    `-- times2_impl.h
|-- python
|    |-- CMakeLists.txt
|    |-- __init__.py
|    |-- qa_times2.py
```

Creating a trivial module: The C++ part

- Header files are in `include/arith` directory
- Code is in `lib/times2_impl.cc`, edit it and replace the $<++>$ by values.
  - in `times2_impl()` (constructor
  - in `forecast` (indicate scheduler how many input are requires for how many output items)
  - in `general_work` core of the treatment.
- `make` it (in the `build` directory), and `make test`

Creating a trivial module: initial debugging

- use `printf` (`#include <sdtio.h>`)
- use `make; make test` (from python testbench)
- log output in `Testing/Temporary/LastTest.log`
- Or equivalently: `ctest -V`

Creating a trivial module: gnuradio-companion block

- Now that you have written a valid block, you can create a valid `grc` block
- go up to `gr-arith` directory:
  `gr_modtool makexml times2`
- install it:
  `cd build; sudo make install`
- You can also install the new blocks in a local directory and set environnement variables to indicate where gnuradio-companion should find them (see labs)
- create a simple grc application (use throttle, remove printf)
- run it (warning: no print!)

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Block important function

- Each Gnu radio bloc inherits from the `gr_block` class.
- The `gr_block` class contains the following important function (file `$GNURADIO/include/gnuradio`:

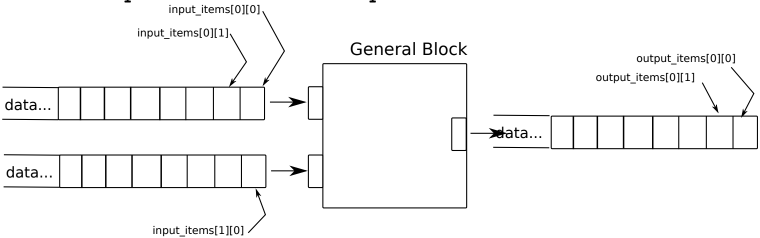
```
void  set_history(unsigned history);
virtual void forecast(int noutput_tems,
            gr_vector_int &ninput_items_required);
 virtual int general_work(int noutput_items,
            gr_vector_int &ninput_items,
            gr_vector_const_void_star &input_items,
            gr_vector_void_star &output_items);
 void consume(int which_input, int how_many_items);
```

function general_work

- The `general_work()` function computes output streams from input streams
- It has 4 arguments
  - `int noutput_items` Number of output items to write on each output stream (all output streams **must** produce the same number of output).
  - `int ninput_items[]` Number of input items to read in each input stream
  - `void* intput_items[]` Vectors of pointers to elements of the input stream(s), i.e., element *i* of this vector points to the i^{th} input stream.
  - `void* output_items[]` Vectors of pointers to elements of the output stream(s), i.e., element *i* of this vector points to the i^{th} output stream.

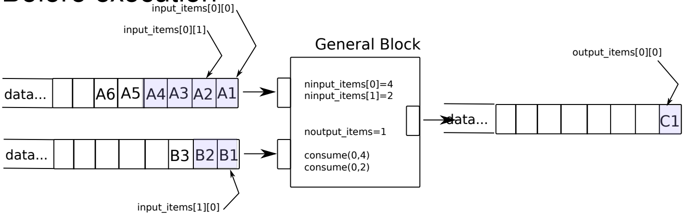
function general_work

- The `general_work` function implement the signal processing algorithm.
- It is called by the scheduler (implicitly, i.e. you do not have to invoke this function explicitly)
- The `consume` function indicates to the scheduler how many data have been consumed once the `general_work` has been executed
- Use of `input_items` and `output_items` vectors:

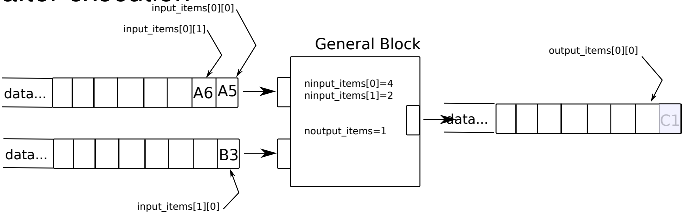


One execution of the block

- Before execution



- after execution



What the code of `work` function could be

- Example: sum the 6 samples in input on the output

```
for(unsigned int j = 0; j < 4; j++) {
 output_items[0][0] += input_items[0][j];
}
for(unsigned int j = 0; j < 2; j++) {
 output_items[0][0] += input_items[1][j];
}
```

- But it is not that simple...
- Gnu radio scheduler invokes the work function for computing a chunks of output (i.e. not one output by one output, in order to avoid too many context switches)
- `noutput_item` stays symbolic, it will be set dynamically during the execution by the scheduler for performance optimization (usually between 4000 and 10000).

What the code of `work` function should be

- add one loop over all `noutput_items` output samples:

```
for (i = 0; i < noutput_items; i++) {
  for(j=0 ; j < 4; j++) {
    output_items[0][i] += input_items[0][4*i+j];
  }
  for(unsigned int j = 0; j < 2; j++) {
    output_items[0][i] += input_items[1][2*i+j];
  }
}
```

- Remember to avoid as much as possible samples copy.

What the code of `work` function really is

- Usual Gnu radio way of writing:

```
const gr_complex *in1 = (const gr_complex*)input_items[0];
const gr_complex *in2 = (const gr_complex*)input_items[1];
gr_complex *out = (gr_complex*)output_items[0];

for (i = 0; i < noutput_items; i++) {
  for(j=0 ; j < 4; j++) {
    *out += *in1++;
  }
  for(unsigned int j = 0; j < 2; j++) {
    *out += *in2++;
  }
  *out++;
}
```

forecast function

- `forecast()` is a function which tells the scheduler how many input items are required to produce `noutput_items` output items.
- In most of the case, they are the same:

```
void
    my_general_block::forecast (int noutput_items,
                                gr_vector_int &ninput_items_required
    {
      ninput_items_required[0] = noutput_items;
    }
```

- It is used as an information by the scheduler to schedule the executions of the different blocs so as to prevent starvation or buffer overflows.

consume function

- The `consume (int which_input, int how_many_items)` function tells the scheduler that `how_many_items` of input stream `which_input` were consumed.
- This function should be called at the end of `general_work()`, after all processing is finished
- `consume_each (int how_many_items)` can be used it the number of items to consume is the same on each input streams

summary: code for my_general_block

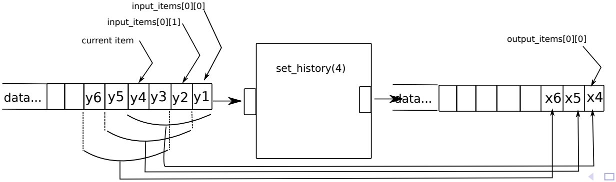
```
 my_general_block::general_work (int noutput_items,
             gr_vector_int &ninput_items,
             gr_vector_const_void_star &input_items,
             gr_vector_void_star &output_items)
{
  const gr_complex *in1 = (const gr_complex*)input_items[0];
  const gr_complex *in2 = (const gr_complex*)input_items[1];
  gr_complex *out = (gr_complex*)output_items[0];

  for (i = 0; i < noutput_items; i++) {
    for(j=0 ; j < 4; j++) {
      *out += *in1++;
    }
    for(unsigned int j = 0; j < 2; j++) {
      *out += *in2++;
    }
    *out++;
  }
  consume(0,4*noutput_items);
  consume(1,4*noutput_items);
}
void
    my_general_block::forecast (int noutput_items,
                       gr_vector_int &ninput_items_required)
    {
      ninput_items_required[0] = 4*noutput_items;
      ninput_items_required[1] = 2*noutput_items;
    }
```

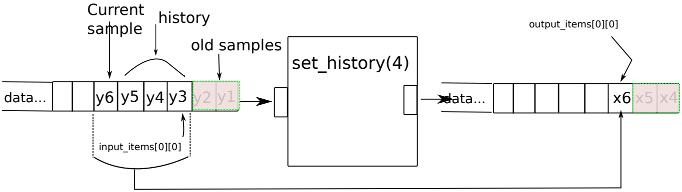
History or pipelined blocs

- Previous example was referred as a block without history in Gnu Radio: *every input is read only once to produce a single output*.
- Or equivalently: each data read is immediately consumed
- Many processing blocs act in a pipeline fashion:
  - produce one output data per input data
  - but... use more than one input data to produce an output data.
- Example of a 4 taps FIR filter:

$$x(i) = \sum_{k=0}^{4} y(i-k)w(k)$$



use of history in blocs



- the `set_history()` function is used by the scheduler to keep some old sample *alive* (or available) to current sample computation.
- `set_history(hist)` means that we are using `hist` sample (including current) to produce current output.
- `input_item[0][0]` points to the oldest sample.
- Usually we shift the input stream: `*in = *(in+hist-1)` such that `*in` point to the current sample.

Other types of blocs

- `gr::sync_block` is derived from `gr::block` and implements a 1:1 block:
  - It has a `work()` function rather than `general_work()` function
  - it omits the unnecessary `ninput_items` parameter, and do not need the `consume_each()` to be called
- `gr::gr_sync_decimator` is used when the number of input items is a fixed multiple of the number of output items.
  - The `gr_sync_decimator` constructor takes a 4th parameter, the decimation factor
  - The user should assume that the number of `ninput_items = noutput_items*decimation`
- `gr::gr_sync_interpolator` is used when the number of output items is a fixed multiple of the number of input items.
  - The `gr_sync_interpolator` constructor takes a 4th parameter, the interpolation factor
  - The user should assume that the number of `ninput_items = noutput_items/interpolation`

GNU Radio scheduler

- Dataflow programming model
- Each block needs a given number of data before running once (i.e. running the `general_work` method)
- the `forecast` method of a bloc indicate this information to the scheduler.
- The scheduler decides to group several execution of each bloc and provides a trade-off between performance efficiency and buffer size between blocs.

Table of Contents

Message passing protocols

- GNU Radio was originally a (infinite) streaming system with no other mechanism to pass data between blocks.
- Not adapted to control data, metadata, and, packet processing
- For solving this problem, gnuradio introduced
  - *Metada files*
  - *Stream tags*
  - *Message passing*
  - All that heavily relying on the polymorphic types

Polymorphic Types: PMT

- Polymorphic Types are opaque data types that are designed as generic containers of data.
- mostly contained in file `pmt.h`

In Python

```
>>> import pmt
>>> P = pmt.from_long(23)
>>> type(P)
<class 'pmt.pmt_swig.swig_int_ptr'>
>>> print P
23
>>> P2 = pmt.from_complex(1j)
>>> type(P2)
<class 'pmt.pmt_swig.swig_int_ptr'>
>>> print P2
0+1i
>>> pmt.is_complex(P2)
True
```

In C++

```
#include <pmt/pmt.h>
// [...]
pmt::pmt_t P = pmt::from_long(23);
std::cout << P << std::endl;
pmt::pmt_t P2 = pmt::from_complex(gr_complex(0, 1));
            // Alternatively: pmt::from_complex(0, 1)
std::cout << P2 << std::endl;
std::cout << pmt::is_complex(P2) << std::endl;
```

PMT function

- Creating, extracting; `pmt::from_<type>`, `pmt::to_<type>`.
- Test, comparison `pmt::is_<type>`
- PMT dictionaries : lists of `key:value` pairs, function for various dictionary operation:

```
pmt_t pmt::dict_add(const pmt_t &dict, const pmt_t &key,
                    const pmt_t &value)#
```

- PMT vectors come in two forms: vectors of PMTs and vectors of uniform data., example of operation:

```
void pmt::vector_set(pmt_t vector, size_t k, pmt_t obj)
```

- The PMT library has methods to serialize data into a string buffer or a string, example:

```
bool pmt::serialize(pmt_t obj, std::streambuf &sink)
```

Metadata files

- Metadata files is a tool to handle metadata on streams (i.e. additional information on samples: rate, types etc.).
- Metadata are present in sample file header.
- There are two kind of Metadata files:
  - inline: headers are inline with the data in the same file.
  - detached: headers are in a separate header file from the data.

Metadata files

- We write metadata files using `gr::blocks::file_meta_sink` and read metadata files using `gr::blocks::file_meta_source`.
- The information that can be contained in a header:
  - `version`: (char) version number (usually set to `METADATA_VERSION`)
  - `rx_rate`: (double) Stream's sample rate
  - `rx_time`: (`pmt::pmt_t pair - (uint64_t, double)`) Time stamp
  - `size`: (int) item size in bytes - reflects vector length if any.
  - `type`: (int) data type
  - `cplx`: (bool) true if data is complex
  - `strt`: (`uint64_t`) start of data relative to current header
  - `bytes`: (`uint64_t`) size of following data segment in bytes

Metadata files: example

- The file metadata header is created with a PMT dictionary of `key:value` pairs,
- then the dictionary is serialized into a string to be written to file.
- Simplest example (`mp`, *make PMT* it a shortcut to the correct `from_<type>` function):

```
const char METADATA_VERSION = 0x0;
pmt::pmt_t header;
header = pmt::make_dict();
header = pmt::dict_add(header, pmt::mp("version"),
                       pmt::mp(METADATA_VERSION));
header = pmt::dict_add(header, pmt::mp("rx_rate"),
                       pmt::mp(samp_rate));
std::string hdr_str = pmt::serialize_str(header);
```

Stream Tags

- Stream tags are an isosynchronous data stream that runs parallel to the main data stream.
- A stream tag:
  - is generated by a block's work function
  - from there on flows downstream with a particular sample
  - until it reaches a sink or is forced to stop propagating by another block.
- Stream tags allows other blocks to identify that an event or action has occurred or should occur on a particular item.

Stream Tags

- An extension to the API of `gr::block` is provided to keep track of absolute item numbers:
  - Each input stream is associated with a concept of the 'number of items read' and
  - each output stream has a 'number of items written.'
- the `gr::tag_t` data type is added to define tags which is composed of the following attributes:
  - `offset`: The offset, in absolute item time, of the tag in the data stream
  - `key`: the PMT symbol identifying the type of tag
  - `value`: the PMT holding the data of the tag.
  - `srcid`: (optional) the PMT symbol identifying the block which created the tag
- Example of stream tag API function:

```
void add_item_tag(unsigned int which_output, const tag_t &tag);
```

Message passing

- Stream tags are useful to pass information with samples but it only goes in one direction
- We need message passing
  - to allow blocks downstream to communicate back to blocks upstream.
  - to communicate back and forth between external applications and GNU Radio(e.g. MAC layer)
- The message passing interface API has been added to the `gr::basic_block` module.
- Message passing between block is identified by dashed lines in `gnuradio-companion` (- - - - - - -)

Message passing

- A block has to declare its input and output message ports in its constructor:

```
void message_port_register_in(pmt::pmt_t port_id)
void message_port_register_out(pmt::pmt_t port_id)
```

- The ports are now identifiable by that a global port name.
- Other blocks may want to post a messages,
- They must subscribe to the port and the publish message on it

```
void message_port_pub(pmt::pmt_t port_id,
pmt::pmt_t msg);
void message_port_sub(pmt::pmt_t port_id,
pmt::pmt_t target);
```