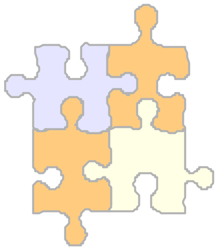
RooFit Programmers Tutorial

Wouter Verkerke (UC Santa Barbara)
David Kirkby (UC Irvine)

RooFit design philosophy



Mathematical concepts as C++ objects

General rules for RooFit classes

RooFit core design philosophy

- Mathematical objects are represented as C++ objects

Mathematical concept		RooFit class
variable	x	`RooRealVar`
function	$f(x)$	`RooAbsReal`
PDF	$f(x)$	`RooAbsPdf`
space point	$\vec{x}$	`RooArgSet`
integral	$\int_{x_{\min}}^{x_{\max}} f(x)dx$	`RooRealIntegral`
list of space points		`RooAbsData`

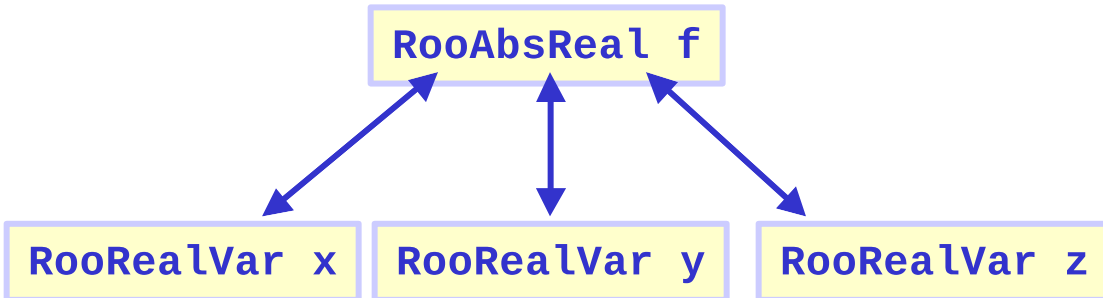
RooFit core design philosophy

- Represent relations between variables and functions as client/server links between objects

Math

$$f(x,y,z)$$

RooFit diagram



RooFit code

```
RooRealVar x("x","x",5) ;
RooRealVar y("y","y",5) ;
RooRealVar z("z","z",5) ;
RooBogusFunction f("f","f",x,y,z) ;
```

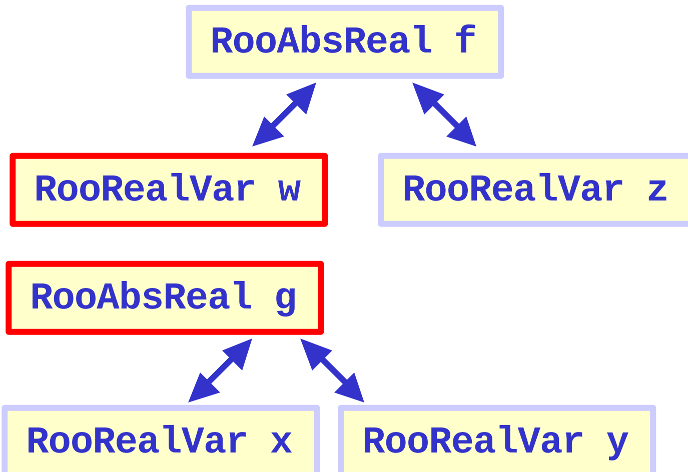
RooFit core design philosophy

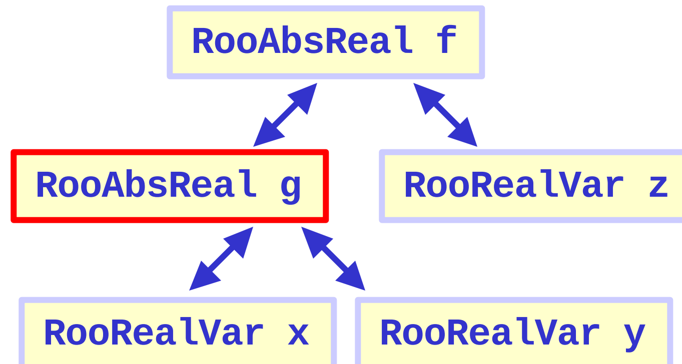
- Composite functions → Composite objects

Math

$$f(w,z) \quad g(x,y) \quad \longrightarrow \quad f(g(x,y),z) = f(x,y,z)$$

RooFit diagram





RooFit code

```
RooRealVar x("x","x",2) ;
RooRealVar y("y","y",3) ;
RooGooFunc g("g","g",x,y) ;

RooRealVar w("w","w",0) ;
RooRealVar z("z","z",5) ;
RooFooFunc f("f","f",w,z) ;
```

```
RooRealVar x("x","x",2) ;
RooRealVar y("y","y",3) ;
RooGooFunc g("g","g",x,y) ;

RooRealVar z("z","z",5) ;
RooFooFunc f("f","f",g,z) ;
```

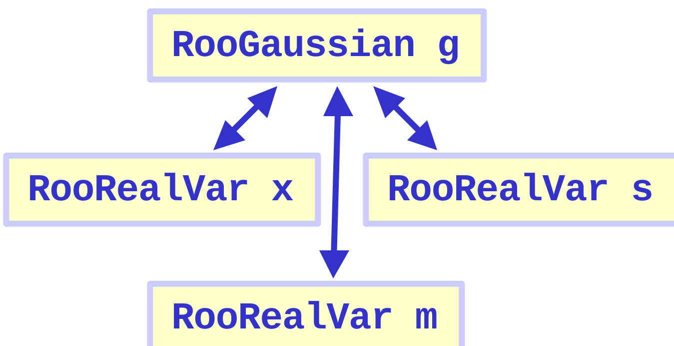
RooFit core design philosophy

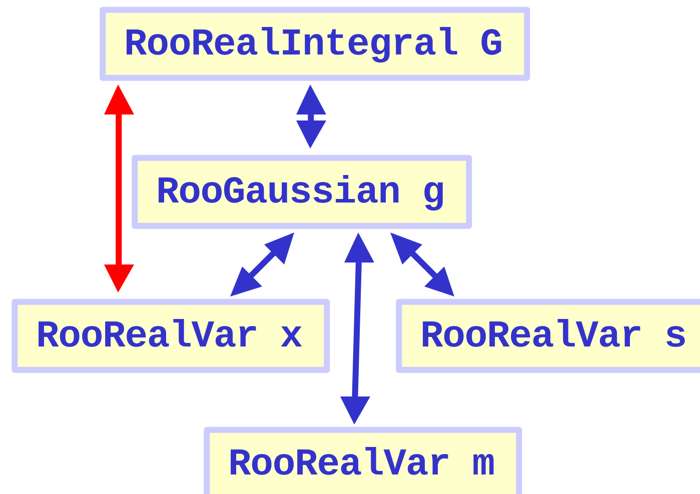
- Represent integral as an object,
  instead of representing integration as an action

Math

$$g(x,m,s) \longrightarrow \int_{x_{\min}}^{x_{\max}} g(x,m,s)\,dx = G(m,s,x_{\min},x_{\max})$$

RooFit diagram





RooFit code

```
RooRealVar x("x","x",2,-10,10)
RooRealVar s("s","s",3) ;
RooRealVar m("m","m",0) ;
RooGaussian g("g","g",x,m,s)
```

```
RooAbsReal *G =
     g.createIntegral(x) ;
```

RooFit designed goals for easy-of-use in macros

- Mathematical concepts mimicked as much as possible in class design
  - Intuitive to use
- Every object that can be constructed through composition should be fully functional
  - No implementation level restrictions
  - No zombie objects

Only current exception: convolutions

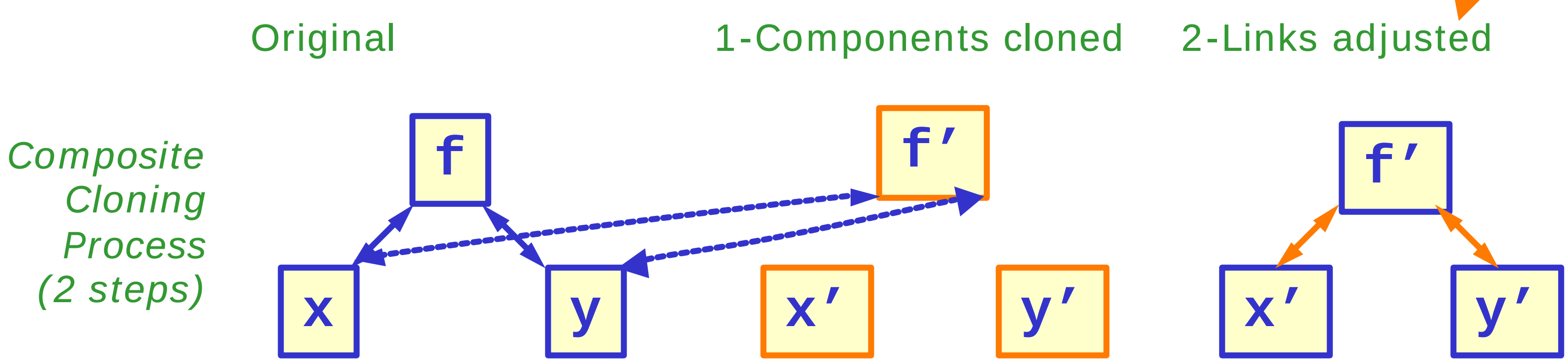
- All methods must work on all objects
  - Integration, toyMC generation, etc
  - No half-working classes

RooFit designed for easy-of-use in macros

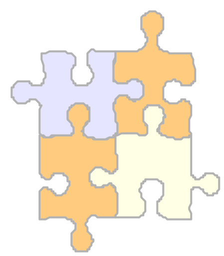
- At the same time, RooFit class structure designed to facilitate lightweight implementation-level classes
  - All value representing classes inherit from a common base class: **`RooAbsArg`**
- **`RooAbsArg`** and other intermediate abstract base classes handle bulk of the logistics
  - In most cases only *one* method is required: **`evaluate()`**
  - Implementation of common techniques such as integral calculation or ToyMC generator not mandatory
  - Base classes provide default numerical/generic methods
- RooAbsArg implementation must follow a minimal set of coding rules

Coding rules for RooAbsArg derived classes

1. Write well-behaved classes.
   - RooAbsArg objects classes are not glorified **`struct`**s, well-defined copy semantics are essential: write a functional copy constructor
2. Every concrete class must have a **`clone()`** method
3. Do not store pointers to other **`RooAbsArg`** objects
   - Many high-level RooFit operations, such as plotting, fitting and generating, clone composite PDFs and need to readjust links
   - Use **`RooXXXProxy`** classes to store references



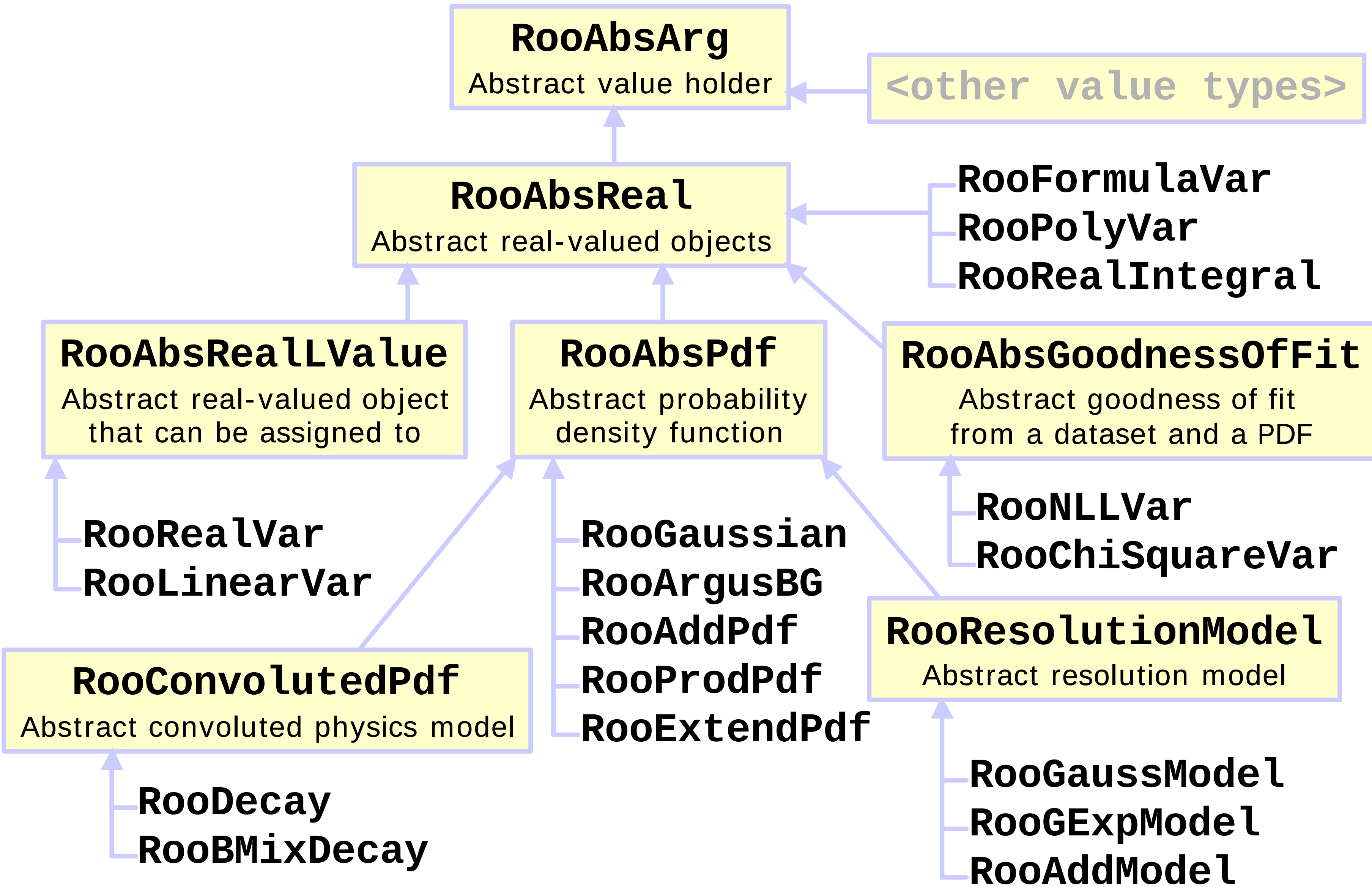
Class hierarchy



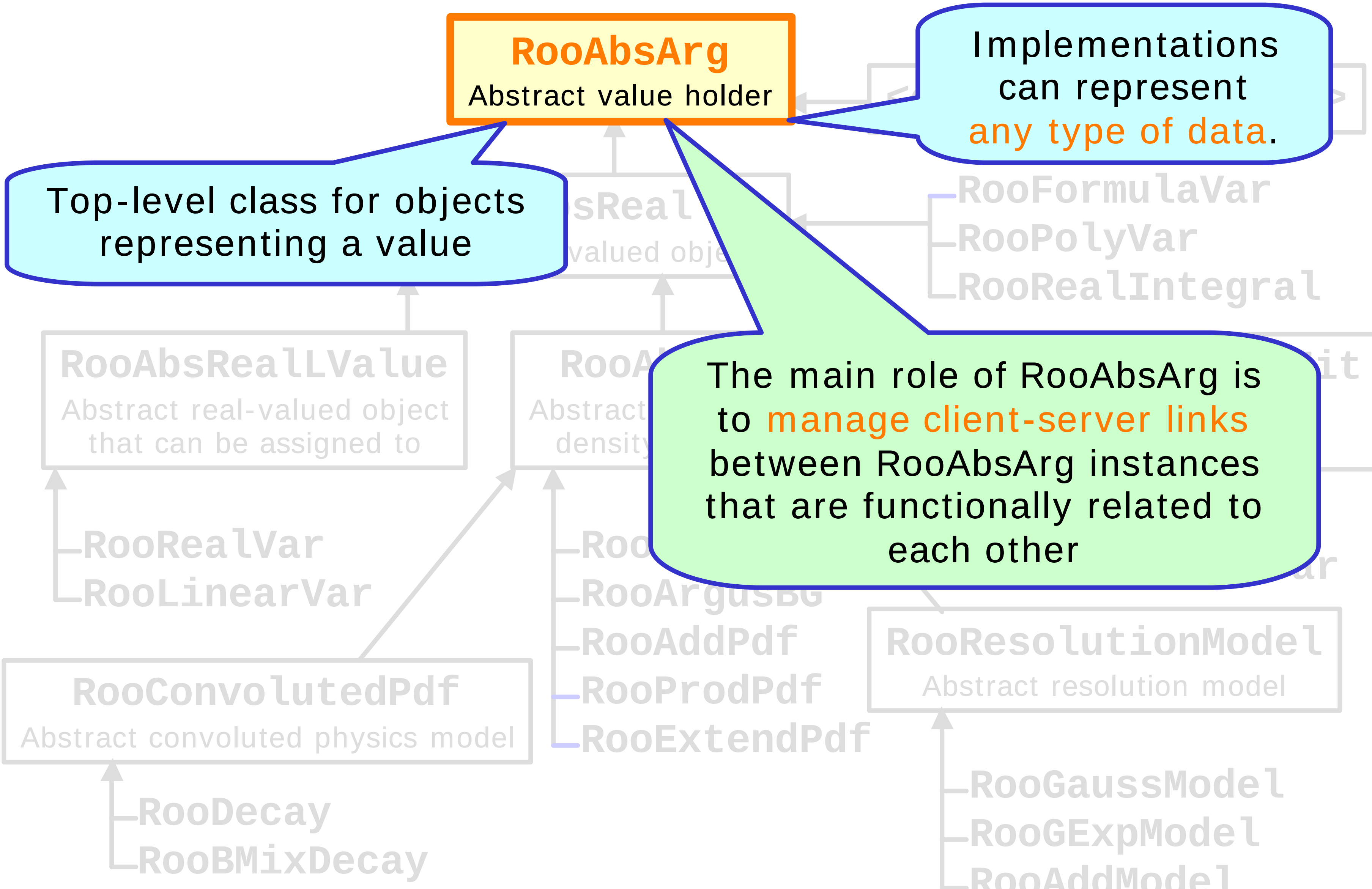
Introduction of various abstract base classes

Coding examples

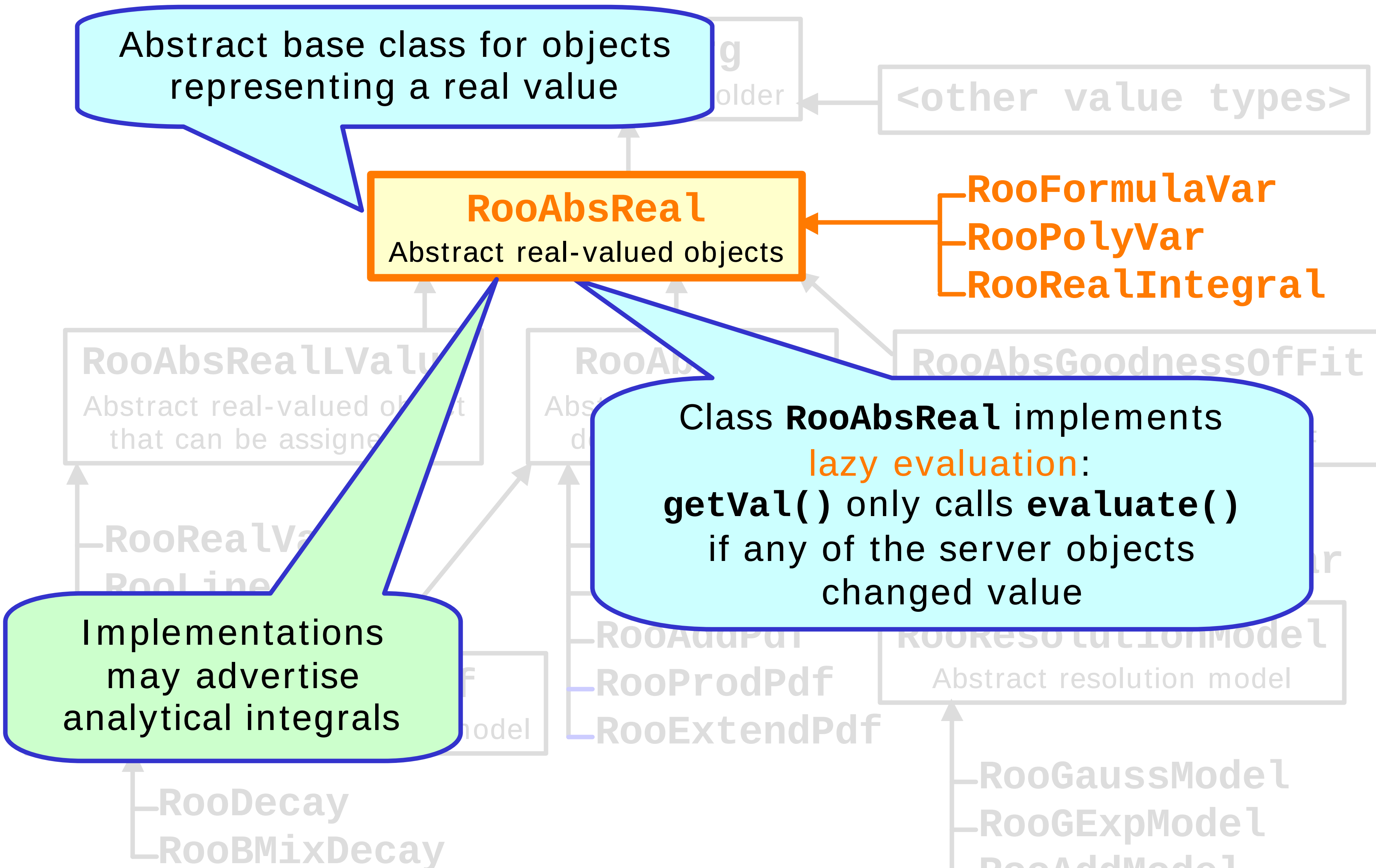
Hierarchy of classes representing a value or function



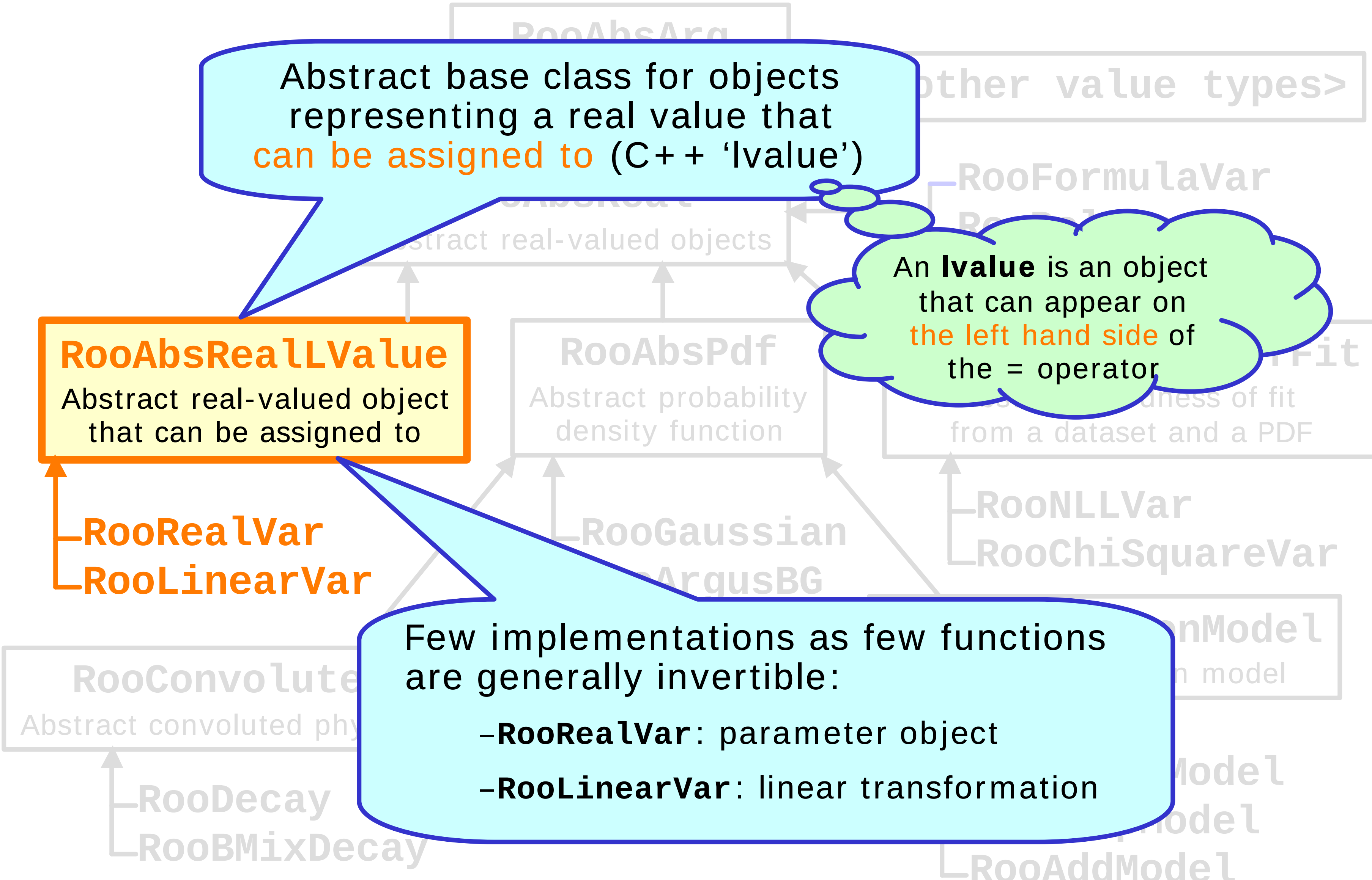
Class **RooAbsArg**



Class **RooAbsReal**

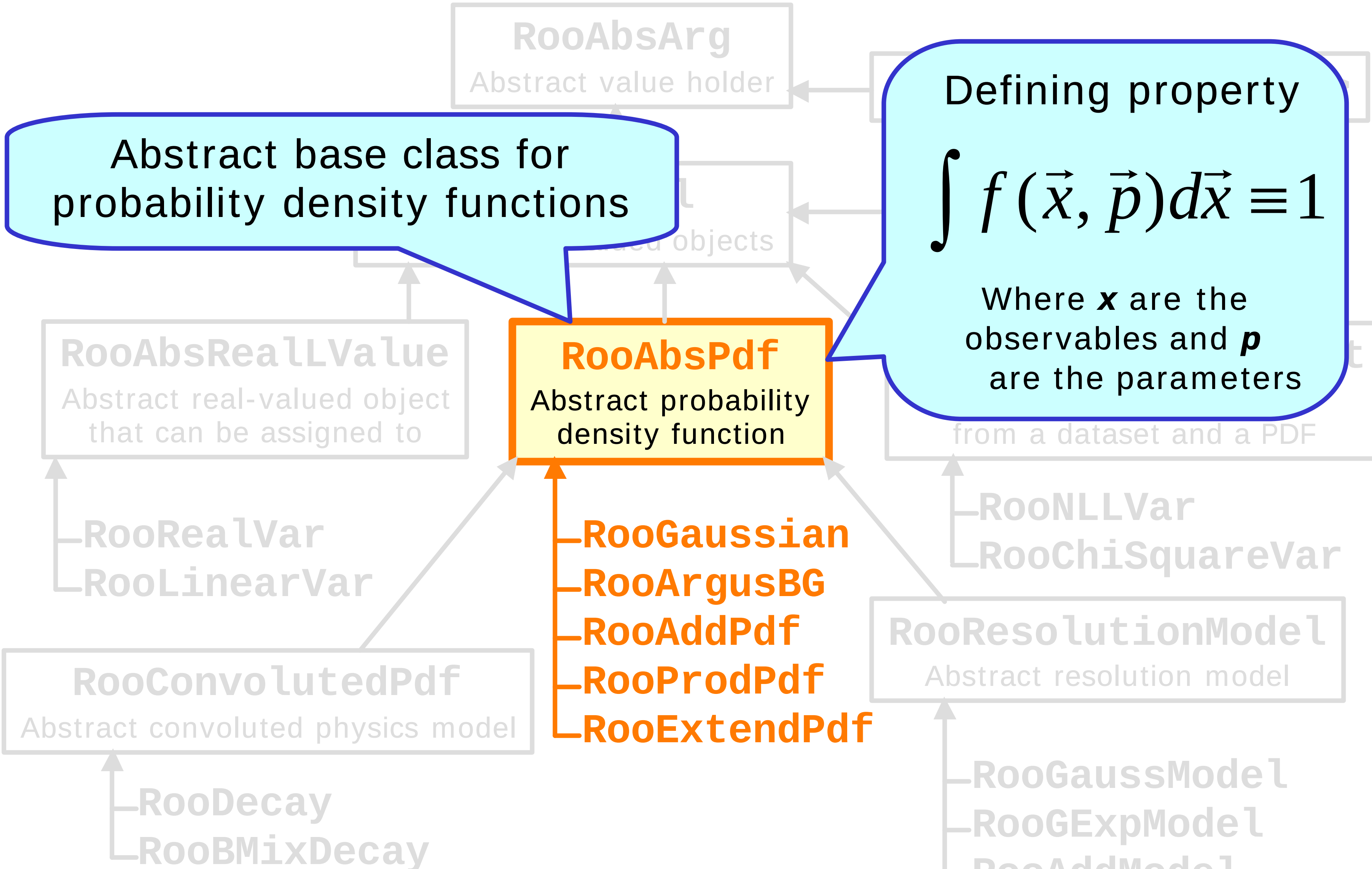


Class **RooAbsRealLValue**



Wouter Verkerke, UCSB

Class **RooAbsPdf**



Class RooConvolutedPdf

Implements $f_i(dt,\ldots) \otimes R(dt,\ldots)$

RooResolutionModel

$$P(dt,\ldots) = \sum_k c_k(\ldots)\left(f_k(dt,\ldots) \otimes R(dt,\ldots) \right)$$

RooConvolutedPdf (physics model)

Implements c_k , declares list of f_k needed

No convolutions calculated in this class!

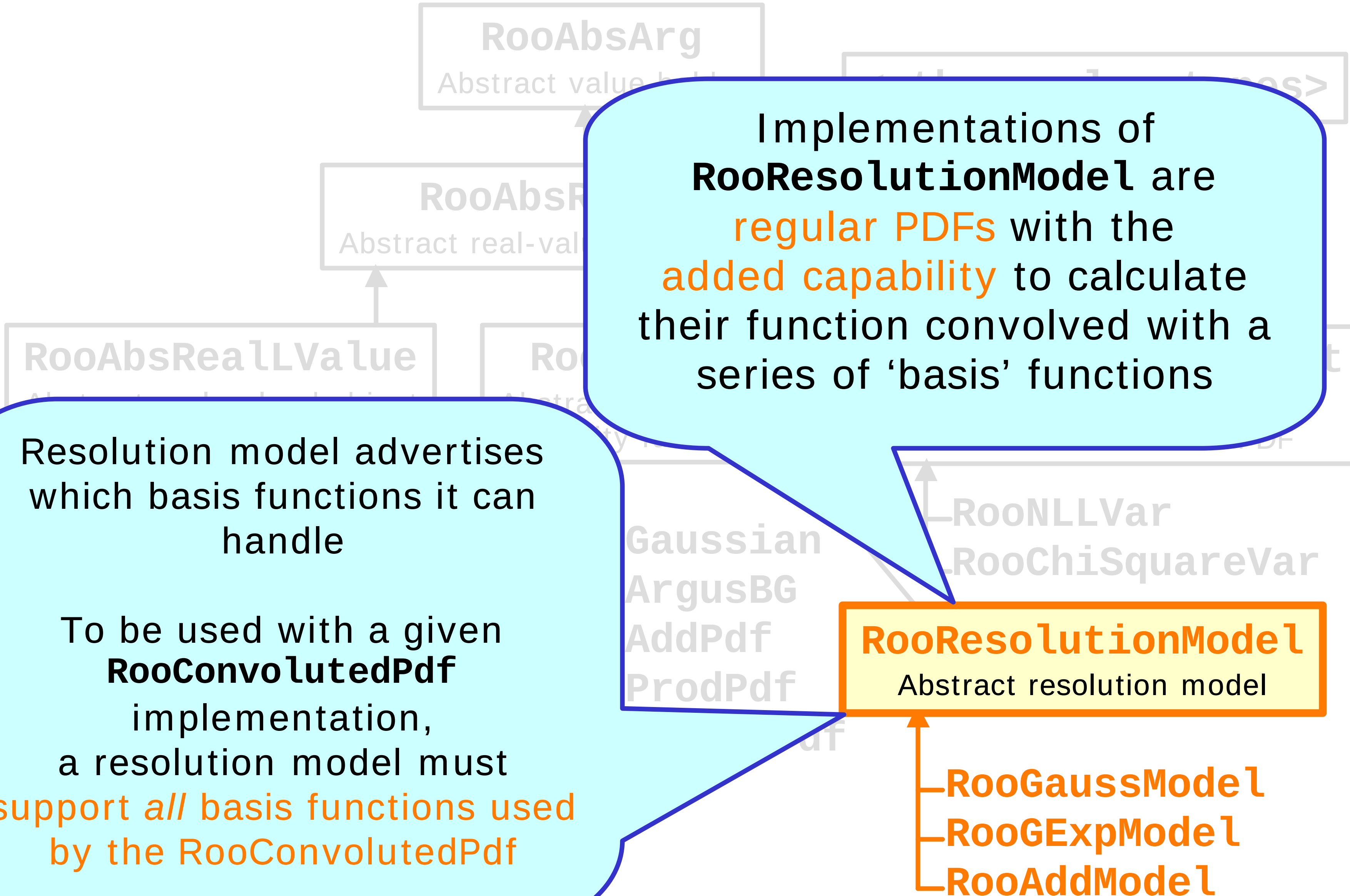
RooConvolutedPdf

Abstract convoluted physics model

- **RooDecay**
- **RooBMixDecay**

Abstract base class for PDFs that can be convoluted with a resolution model

Class **RooResolutionModel**



Implementations of **RooResolutionModel** are regular PDFs with the added capability to calculate their function convolved with a series of 'basis' functions

Resolution model advertises which basis functions it can handle

To be used with a given **RooConvolutedPdf** implementation, a resolution model must support *all* basis functions used by the RooConvolutedPdf

Class **RooAbsGoodnessOfFit**

Provides the framework for efficient calculation of goodness-of-fit quantities.

A goodness-of-fit quantity is a function that is calculated from

- A dataset
- the PDF value for each point in that dataset

RooAbsGoodnessOfFit

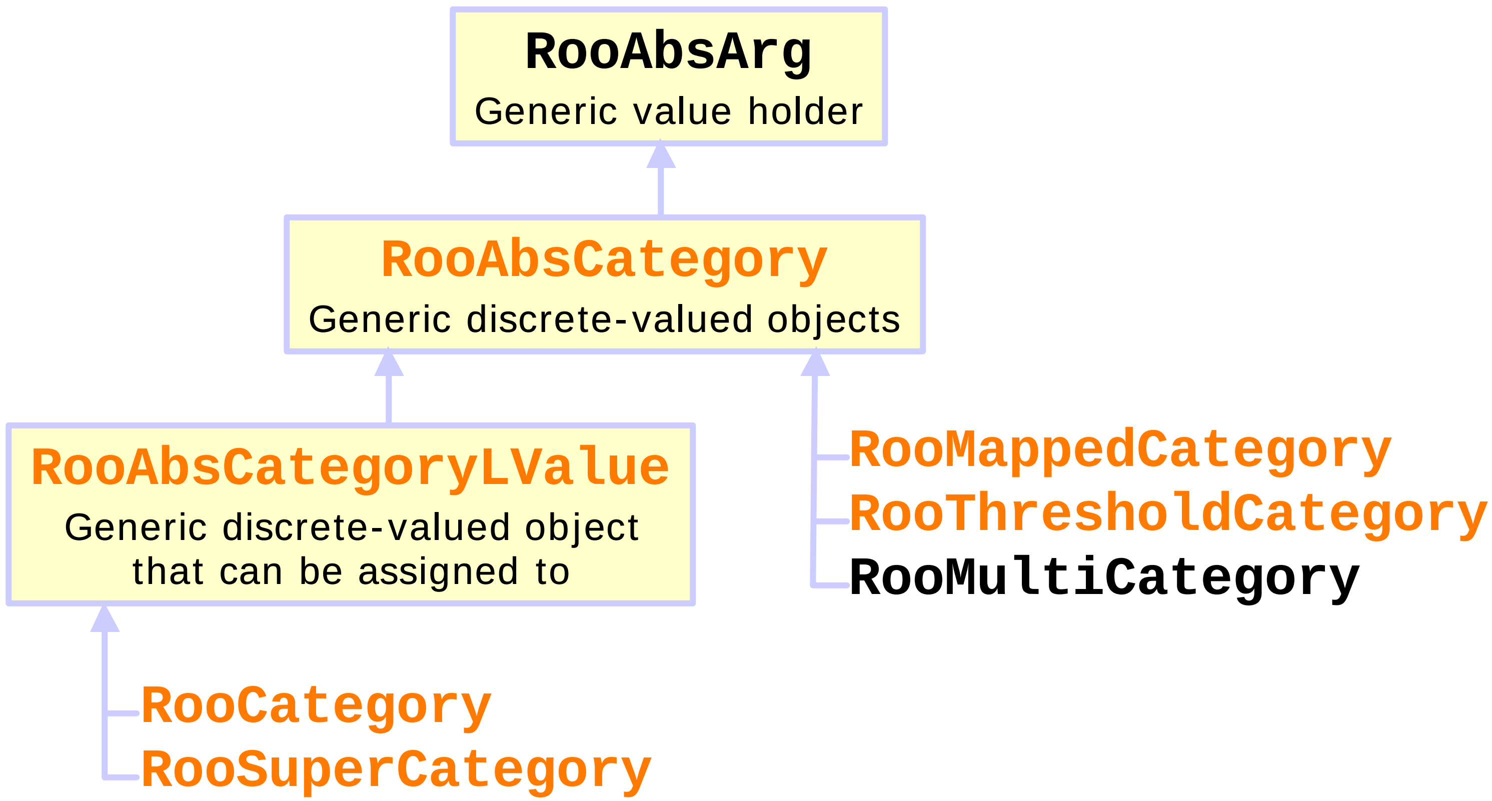
Abstract goodness of fit from a dataset and a PDF

- **RooNLLVar**
- **RooChiSquareVar**

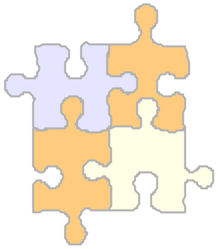
Built-in support for

- **Automatic constant-term optimization** activated when used by RooMinimizer(MINUIT)
- **Parallel execution on multi-CPU hosts**
- Efficient **calculation of RooSimultaneous** PDFs

Class tree for discrete-valued objects



Code examples



Implementing a RooAbsReal

Providing analytical integrals

Implementing a RooAbsPdf

Providing an internal generator

Implementing a RooConvolutedPdf/RooResolutionModel

Implementing a RooAbsGoodnessOfFit

Writing a real-valued function – class **RooAbsReal**

- Class declaration

```
class RooUserFunc : public RooAbsReal {
public:
  RooUserFunc(const char      e, const char *title,
              RooAb          x, RooAbsReal& _mean,
                             _sigma);
                               er,

  virtual TObject* clone(const char* newname) const {
          return new RooUserFunc(*this,newname);
  }
  inline virtual ~RooUserFunc() { }

protected:
  RooRealProxy x ;
  RooRealProxy mean ;
  RooRealProxy sigma ;

  Double_t evaluate() const ;

private:
  ClassDef(RooUserFunc,0) // Gaussian PDF
};
```

Real-valued functions inherit from **RooAbsReal**

Writing a function – class **RooAbsReal**

- Mandatory methods

- Constructor
- Copy constructor
- Clone
- Destructor
- **evaluate**
  Calculates your PDF return value

```
class RooUserFunc : public RooAbsPdf {
public:
  RooUserFunc(const char *name, const char *title,
              RooAbsReal& _x, RooAbsReal& _mean,
               RooAbsReal& _sigma);
  RooUserFunc(const RooUserFunc& other,
              const char* name=0) ;
  virtual TObject* clone(const char* newname) const {
          return new RooUserFunc(*this,newname);
  }
  inline virtual ~RooUserFunc() { }

protected:
  RooRealProxy x ;
  RooRealProxy mean ;
  RooRealProxy sigma ;

  Double_t evaluate() const ;

private:
  ClassDef(RooUserFunc,0) // Gaussian PDF
};
```

Use copy ctor in **clone()**

Writing a function – class **RooAbsReal**

- Constructor arguments

```
class RooUserFunc : public RooAbsPdf {
public:
  RooUserFunc(const char *name, const char *title,
                    RooAbsReal& _x, RooAbsReal& _mean,
                    RooAbsReal& _sigma);
  RooU...(const RooUserFunc& other,
                    const char* name=0) ;
...                                            ) const {
private:
  ClassDef(RooUserFunc,0) // Gaussian PDF
};
```

Try to be as generic as possible, i.e.

Use **RooAbsReal&** to receive real-valued arguments
Use **RooAbsCategory&** to receive discrete-valued arguments

Allows user to plug in either
a variable (**RooRealVar**) or a function (**RooAbsReal**)

Writing a function – class **RooAbsReal**

- Storing **RooAbsArg** references

Always use proxies to store RooAbsArg references:

RooRealProxy	for	**RooAbsReal**
RooCategoryProxy	for	**RooAbsCategory**
RooSetProxy	for	a set of **RooAbsArgs**
RooListProxy	for	a list of **RooAbsArgs**

```
r *title,
& _mean,

name) const {
    return new RooUserFunc(*this,newname);

line virtual ~RooUserFunc() { }

protected:
  RooRealProxy x ;
  RooRealProxy mean ;
  RooRealProxy sigma ;

  Double_t evaluate() const ;

private:
  ClassDef(RooUserFunc,0) // Gaussian PDF
};
```

Storing references in proxies allows RooFit to adjust pointers

This is essential for cloning of composite objects

Writing a function – class **RooAbsReal**

- ROOT-CINT dictionary methods

```
class RooUserFunc : public RooAbsPdf {
public:
  RooUserFunc(const char *name, const char *title,
              RooAbsReal& _x, RooAbsReal& _mean,
              RooAbsReal& _sigma);
  RooUserFunc(const RooUserFunc& other,
              const char* name=0) ;
  virtual TObject* clone(const char* newname) const {
          return new RooUserFunc(*this,newname);
  }
  inline virtual ~RooUserFunc()

protected:
  RooRealProxy x ;

private:
  ClassDef(RooUserFunc,1) // Gaussian PDF
};
```

Don't forget ROOT **ClassDef** macro
No semi-colon at end of line!

Description here will be used in auto-generated **THtml** documentation

Writing a function – class **RooAbsReal**

- Constructor implementation

```
RooUserFunc::RooUserFunc(const char *name, const char *title,
                         RooAbsReal& _x, RooAbsReal& _mean,
                         RooAbsReal& _sigma) :
  RooAbsPdf(name,title),
  x("x","Dependent",this,_x),
  mean("mean","Mean",this,_mean),
  sigma("sigma","Width",this,_sigma)
{
```

Initialize the proxies from the **RooAbsArg** method arguments

Name and title are for description only

Pointer to owning object is needed to register proxy

```
rFunc::Roo   rFunc(const
bsPdf(othe   e),
",this,othe
mean("mean",thi   er.mean),
sigma("sigma",t   her.sigma)
{

() const
{
  Double_t arg= x - mean;
  return exp(-0.5*arg*arg/(sigma*sigma)) ;
}
```

Writing a function – class **RooAbsReal**

- **Implement a copy constructor!**

```
RooUserFunc::RooUserFunc(const char *name, const char *title,
                         RooAbsReal& _x, RooAbsReal& _mean,
                         RooAbsReal& _sigma) :
  RooAbsPdf(name,title),
```

In the class copy constructor,
call all *proxy copy constructors*

```
}

RooUserFunc::RooU      nc(const RooUserFunc& other,
                          const char* name) :
  RooAbsPdf(other, name),
  x(this,other.x),
  mean(this,other.mean),
  sigma(this,other.sigma)
{
}

Double_t RooU
{
  Double_t arg
  return exp(-              gma)) ;
}
```

Pointer to owning object is (again) needed to register proxy

Writing a function – class **RooAbsReal**

- Write evaluate function

```
RooUserFunc::RooUserFunc(const char *name, const char *title,
                         RooAbsReal& _x, RooAbsReal& _mean,
                         RooAbsReal& _sigma) :
  RooAbsPdf(name,title),
  x("x","Dependent",this,_x),
  mean("mean","Mean",this,_mean),
  sigma("sigma","Width",this,_sigma)
{
}

RooUserFunc::RooUserFunc(const RooUserFunc& other,
                                const char* name) :
  RooAbsPdf(other,name),
  x("x",this,other.x),
  mean("mean",this,other.mean),
```

In **evaluate()**, calculate and return the function value

```
Double_t RooUserFunc::evaluate() const
{
  Double_t arg= x - mean;
  return exp(-0.5*arg*arg/(sigma*sigma)) ;
}
```

Working with proxies

- **RooRealProxy/RooCategoryProxy** objects automatically cast to the value type they represent
  - Use as if they were fundamental data types

```
RooRealProxy x ;
Double_t func = x*x ;
```

Use as **Double_t**

```
RooCategoryProxy c ;
if (c==“bogus”) {…}
```

Use as **const char***

- To access the proxied **RooAbsReal/RooAbsCategory** object use the **arg()** method

```
RooRealProxy x ;
RooCategoryProxy c ;

RooAbsReal& xarg = x.arg() ;
RooAbsCategory& carg = c.arg() ;
```

NB: the value or **arg()** may change during the lifetime of the object (e.g. if a composite cloning operation was performed)

- Set and list proxy operation completely transparent
  - Use as if they were **RooArgSet/RooArgList** objects

Lazy function evaluation & caching

- Method getVal() does not always call evaluate()
  - Each RooAbsReal object caches its last calculated function value
  - If none of the dependent values changed, no need to recalculate

- Proxies are used to track changes in objects
  - Whenever a RooAbsArg changes value,
    it notifies all its client objects that recalculation is needed
  - Messages passed via client/server links that are installed by proxies
  - Only if recalculate flag is set getVal() will call evaluate()

- Redundant calculations are automatically avoided
  - Efficient optimization technique for expensive objects like integrals
  - No need to hand-code similar optimization in function code:
    evaluate() is only called when necessary

Writing a function – analytical integrals

- **Analytical integrals are optional!**
- Implementation of analytical integrals is separated in two steps
  - Advertisement of available (partial) integrals:
  - Implementation of partial integrals
- Advertising integrals: **getAnalyticalIntegral()**

Integration is requested over all variables in set **allVars**

```
Int_t RooUserFunc::getAnalyticalIntegral(
                    RooArgSet& allVars, RooArgSet& analVars) const
{
  if (matchArgs(allVars,analVars,x)) return 1 ;
  return 0 ;
}
```

Task of **getAnalyticalIntegral()**:

1) find the *largest subset* that function can integrate analytically
2) Copy largest subset into analVars
3) Return unique identification code for this integral

Writing a function – advertising integrals

Task of **getAnalyticalIntegral()**:

1) find the *largest subset* that function can integrate analytically
2) Copy largest subset into analVars
3) Return unique identification code for this integral

```
Int_t RooUserFunc::getAnalyticalIntegral(
                       RooArgSet& allVars, RooArgSet& analVars) const
{
  if (matchArgs(allVars,analVars,x)) return 1 ;
  return 0 ;
}
```

Utility method **matchArgs()** does all the work for you:

If **allVars** contains the variable held in proxy **x**
variable is copied to **analVars** and **matchArgs()** returns **kTRUE**
If not, it returns **kFALSE**

Writing a function – advertising multiple integrals

```
Int_t RooUserFunc::getAnalyticalIntegral(
                      RooArgSet& allVars, RooArgSet& analVars) const
{
 if (matchArgs(allVars,analVars,x,m)) return 3 ;
 if (matchArgs(allVars,analVars,m)) return 2 ;
 if (matchArgs(allVars,analVars,x)) return 1 ;
  return 0 ;
}
```

If multiple integrals are advertised,
test for the largest one first

You may advertise analytical integrals for
both *real-valued* and *discrete-valued* integrands

Writing a function – implementing integrals

- Implementing integrals: **`analyticalIntegral()`**
  - One entry point for *all* advertised integrals

Integral identification code assigned by **`getAnalyticalIntegral()`**

```
Double_t RooGaussian::analyticalIntegral(Int_t code) const
{
  static const Double_t root2 = sqrt(2) ;
  static const Double_t rootPiBy2 = sqrt(atan2(0.0,-1.0)/2.0);

  Double_t xscale = root2*sigma;
  return rootPiBy2*sigma*
         (erf((x.max()-mean)/xscale)-erf((x.min()-mean)/xscale));
}
```

Integration limits for real-valued integrands can be accessed via the **`min()`** and **`max()`** method of each proxy

Discrete-valued integrands are always summed over *all* states

Calculating integrals – behind the scenes

- Integrals are calculated by **RooRealIntegral**
  - To create an **RooRealIntegral** for a **RooAbsReal**

```
RooAbsReal* f; // f(x)
RooAbsReal* int_f = f.createIntegral(x) ;

RooAbsReal* g ; // g(x,y)
RooAbsReal* inty_g = g.createIntegral(y) ;
RooAbsReal* intxy_g = g.createIntegral(RooArgSet(x,y)) ;
```

A **RooRealIntegral** is also a **RooAbsReal**

- Tasks of **RooRealIntegral**
  - Structural analysis of composite
  - Negotiate analytical integration with components PDF
  - Provide numerical integration where needed

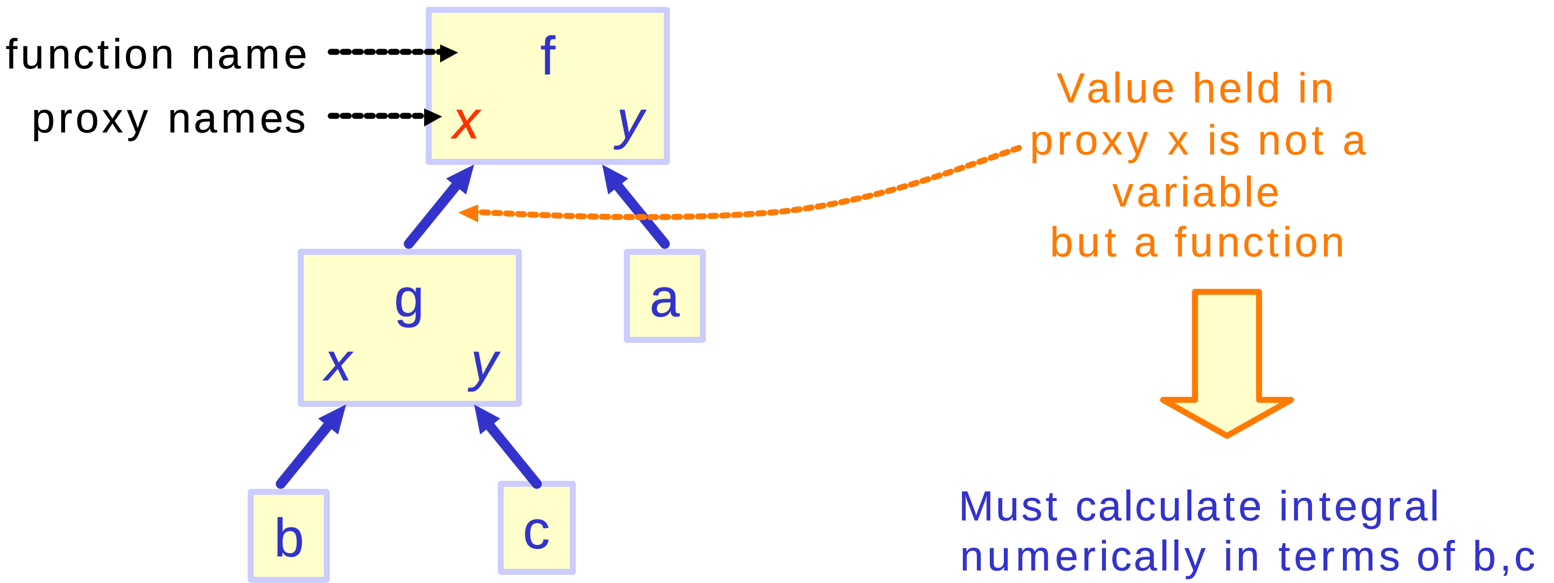
RooRealIntegral is RooFits most complex class!

- **RooRealIntegral** works universally on simple and composite objects

Why advertised analytical integrals are sometimes not used

- Integration variable is not a fundamental
  - Suppose f(x,y) advertises analytical integration over x

$$f(\mathbf{x},a), g(b,c) \rightarrow f(g(b,c),a)$$

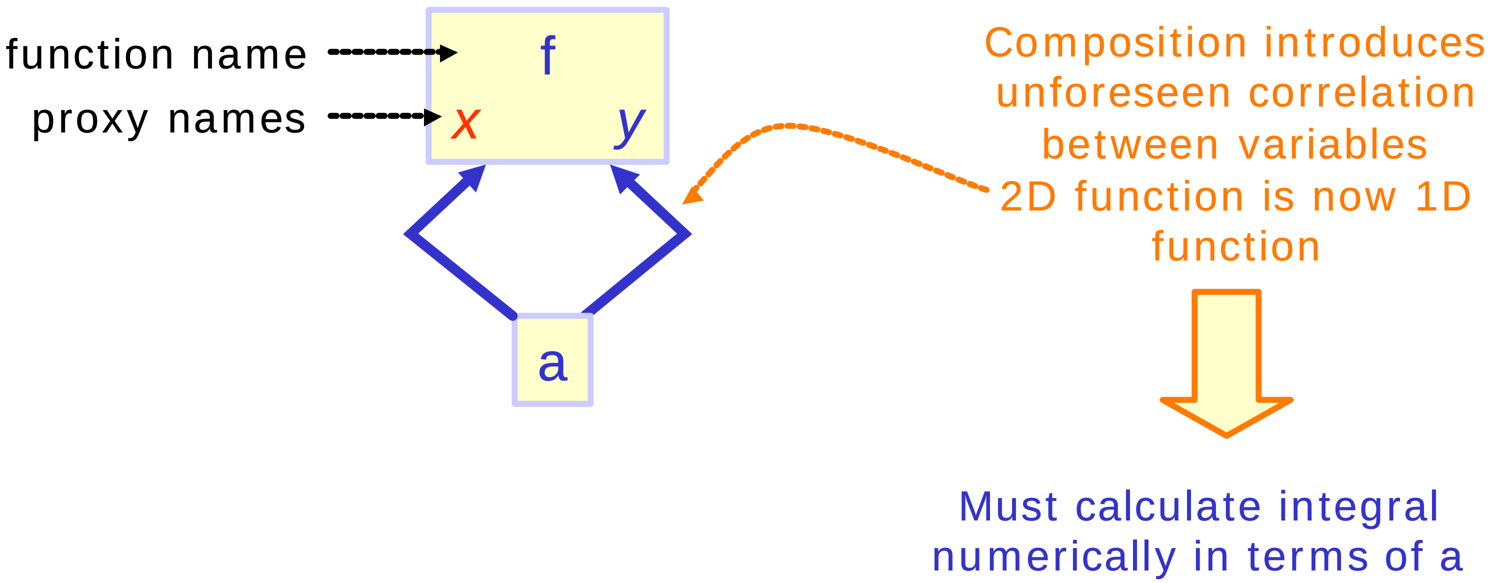


(Exception: g(x,y) is an invertable function (RooAbsRealLValue) with a constant Jacobian term)

Why advertised analytical integrals are sometimes not used

- Function depends more than once on integration variable
  - Suppose f(x,y) advertises analytical integration over x

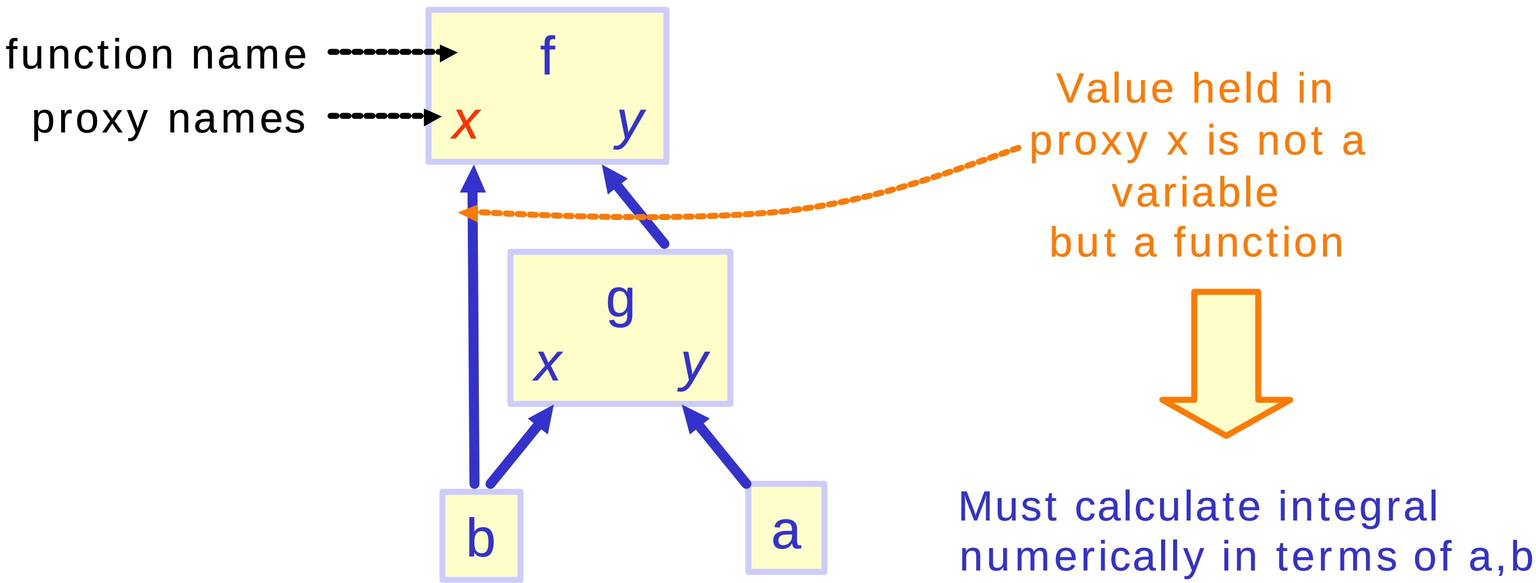
$$f(\boldsymbol{x}, y) \rightarrow f(a, a)$$



Why advertised analytical integrals are sometimes not used

- Function depends more on integration variable via more than one route
  - Suppose f(x,y) advertises analytical integration over x

$$f(\mathbf{x},y),g(a,x) \rightarrow f(x,g(a,x))$$



Class documentation

- General description of the class functionality should be provided at the beginning of your .cc file

Magic line for **THtml**

```
// -- CLASS DESCRIPTION [PDF] --
// Your description goes here
```

PDF Keyword causes class to be classified as PDF class

- First comment block in each function will be picked up by **THtml** as the description of that member function
  - Put some general, sensible description here

Writing a PDF – class **RooAbsPdf**

- Class declaration

```
class RooUserPdf : public RooAbsPdf {
public:
  RooUserFunc(const char *            har *title,
                                                    {
  RooRealProxy mean ;
  RooRealP
  Do
private
  Cla
};
```

PDFs inherit from **RooAbsPdf**

This is the *only* difference with a **RooAbsReal**

RooAbsPdf::getVal() will automatically normalize your return value by dividing it by the integral of the PDF. No further action is needed!

RooRealIntegral used for integral calculation

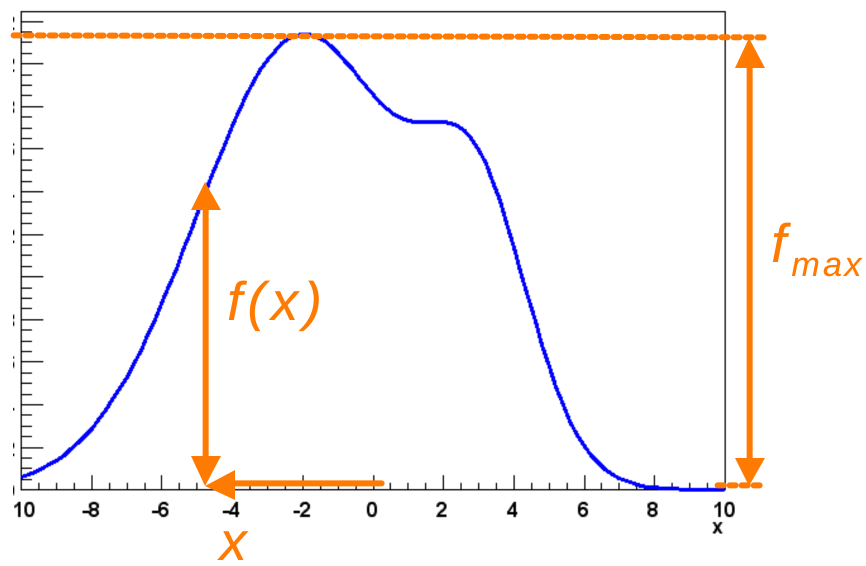
RooAbsPdf owns RRI configured for last normalization configuration. If normalization set Changes, new RRI as created on the fly..

Writing a PDF – Normalization

- Do not ***under any circumstances*** attempt to ***normalize*** your PDF in ***evaluate()*** via ***explicit*** or ***implicit integration***
- You do not know over what variables to normalize
  - In RooFit, parameter/observable distinction is dynamic, a PDF does not have a unique normalization/return value
- You don't even now know how to integrate yourself!
  - Your PDF may be part of a larger composite structure. Variables may be functions, your internal representation may have a difference number of dimensions that the actual composite object.
  - **`RooRealIntegral`** takes proper care of all this
- But you can help!
  - Advertise all partial integrals that you can calculate
  - They will be used in the normalization when appropriate
    - Function calling overhead is minimal

PDF Event generation – Accept/reject method

- By default, toy MC generation from a PDF is performed with accept/reject sampling
  - Determine maximum PDF value by repeated random sample
  - Throw a uniform random value (x) for the observable to be generated
  - Throw another uniform random number between 0 and fmax
    If $ran*f_{max} < f(x)$ accept x as generated event

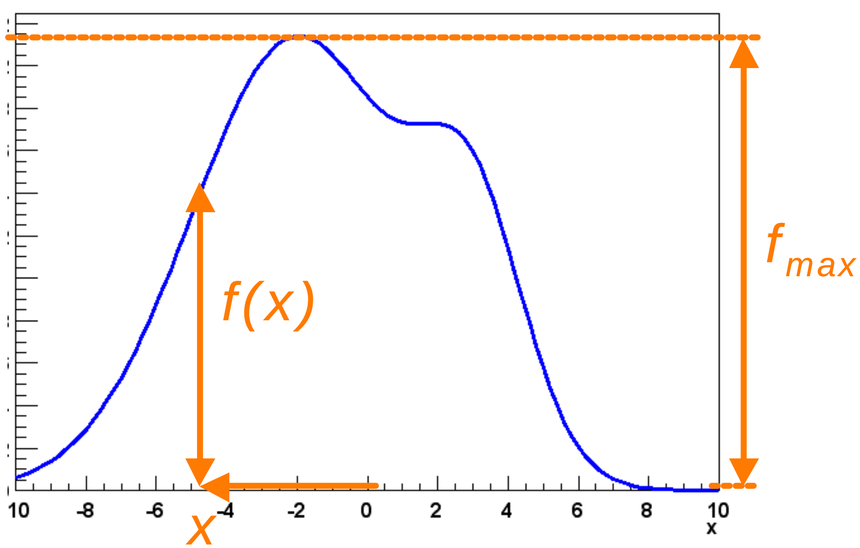


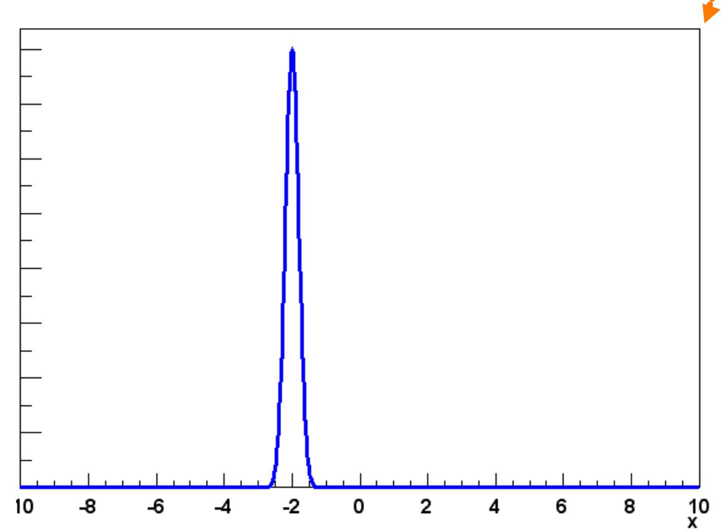
PDF Event generation – Accept/reject method

- Accept/reject method can be very inefficient
  - Generating efficiency is

$$\frac{\int_{x_{\max}}^{x_{\min}} f(x)dx}{(x_{\max} - x_{\min}) \cdot f_{\max}}$$

  - Efficiency is very low for narrowly peaked functions
  - Initial sampling for fmax requires very large trials sets in multiple dimension (~10000000 in 3D)





PDF Event generation – Optimizations

- RooFit 'operator' PDFs provide various optimizations
- **RooProdPdf** – Components PDFs generated separately
  - Breaks down N dimensional problem to n m-dimensional problems
  - Large initial f_{max} sampling penalty not incurred
- **RooAddPdf** – Only one component generated at a time
  - RooAddPdf randomly picks a component PDF to generate for each event. Component probabilities weighted according to fractions
  - Helps to avoid accept/reject sampling on narrowly peaked distributions,if narrow and wide component are separately generated
- **RooSimultaneous** - Only one component generated at a time
  - Technique similar to **RooAddPdf**

PDF Event generation – Internal generators

- For certain PDFs alternate event generation techniques exist that are more efficient that accept/reject sampling
  - Example: Gaussian, exponential,…

- If your PDF has such a technique, you can advertise it
  - Interface similar to analytical integral methods
    ```
    RooAbsPdf::getGenerator()
    RooAbsPdf::initGenerator()
    RooAbsPdf::generateEvent()
    ```

- You don't have to be able to generate *all* observables
  - Generator context can combine accept/reject and internal methods within a single PDF

- This is an optional optimization
  - PDF can always generate events via accept/reject method

Writing a PDF – advertising an internal generator

Task of **getGenerator()**:

1) find the *largest subset* of observables PDF can generate internally
2) Copy largest subset into dirVars
3) Return unique identification code for this integral

```
Int_t RooUserFunc::getGenerator(
  RooArgSet& allVars, RooArgSet& dirVars, Bool_t staticOK) const
{
  if (matchArgs(allVars,dirVars,x)) return 1 ;
  return 0 ;
}
```

Utility method **matchArgs()** does all the work for you:

If **allVars** contains the variable held in proxy **x**
variable is copied to **dirVars** and **matchArgs()** returns **kTRUE**
If not, it returns **kFALSE**

Writing a PDF – advertising an internal generator

- For certain internal generator implementations it can be efficient to do a one-time initialization for each set of generated events
  - Example: precalculate fractions for discrete variables
- Caveat: one-time initialization only safe if no observables are generated from a prototype dataset
  - Only advertise such techniques if staticOK flag is true

```
Int_t RooBMixDecay::getGenerator(const RooArgSet& directVars,
             RooArgSet &generateVars, Bool_t staticInitOK) const
{
  if (staticInitOK) {
    if (matchArgs(directVars,generateVars,t,mix,tag)) return 4 ;
    if (matchArgs(directVars,generateVars,t,mix)) return 3 ;
    if (matchArgs(directVars,generateVars,t,tag)) return 2 ;
  }

  if (matchArgs(directVars,generateVars,_t)) return 1 ;
  return 0 ;
}
```

If you advertise multiple configurations, try the most extensive one first

Writing a PDF – implementing an internal generator

- Implementing a generator: **`generateEvent()`**
  - One entry point for *all* advertised event generators

Generator identification code assigned by **`getGenerator()`**

```
void RooGaussian::generateEvent(Int_t code)
{
  Double_t xgen ;
  while(1) {
    xgen = RooRandom::randomGenerator()->Gaus(mean,sigma);
    if (xgen<x.max() && xgen>x.min()) {
      x = xgen ;
      break;
    }
  }
  return;
}
```

Return generated value by assigning it to the proxy

Writing a PDF – implementing an internal generator

- Static generator initialization: **`initGenerator()`**
  - This function is guaranteed to be call once before each series of **`generateEvent()`** calls with the same configuration

Generator identification code assigned by **`getGenerator()`**

```
void RooBMixDecay::initGenerator(Int_t code)
{
  switch (code) {
  case 2:
    {
      // Calculate the fraction of B0bar events to generate
      Double_t sumInt = RooRealIntegral(…).getVal() ;
      _tagFlav = 1 ; // B0
      Double_t flavInt = RooRealIntegral(…).getVal() ;
      _genFlavFrac = flavInt/sumInt ;
      break ;
    }
  }
}
```

Store your precalculated values in data members

Writing a convoluted PDF – physics/resolution factorization

- Physics model and resolution model are implemented separately in RooFit
  - Factorization achieved via a common set 'basis functions' f_k

Implements $f_i(dt,...) \otimes R(dt,...)$
Also a PDF by itself

RooResolutionModel

$$P(dt,...) = \sum_k c_k(...)\left(f_k(dt,...) \otimes R(dt,...)\right)$$

RooConvolutedPdf (physics model)

- Implements c_k
- Declares list of f_k needed

No magic: You must still calculate the convolution integral yourself, but factorization enhances modularity & flexibility for end user

Writing a convoluted PDF – class **RooConvolutedPdf**

- Class declaration

```
class RooBMixDecay : public RooConvolutedPdf {
public:
```

Convolutable PDF classes inherit from **RooConvolutedPdf** instead of **RooAbsPdf**

```
  RooBMixDecay(const RooBMixDecay& other, const char* name=0);
  virtual TObject* clone(const char* newname) const ;
  virtual ~RooBMixDecay();

  virtual Double_t coefficient(Int_t basisIndex) const ;

protected:
```

Implement **coefficient()** instead of **evaluate()**

```
};
```

Class **RooConvolutedPdf** – Constructor implementation

- Constructor must declare all basis functions used

```
RooBMixDecay::RooBMixDecay(const char *name, const char *title,…) :
  RooConvolutedPdf(name,title,model,t), …
{
  // Constructor
  _basisExp = declareBasis("exp(-abs(@0)/@1)",
                           RooArgList(tau)) ;
  _basisCos = declareBasis("exp(-abs(@0)/@1)*cos(@0*@2)",
                           RooArgList(tau,dm)) ;
}
```

Supply basis function parameters here

Call **declareBasis()** for each basis functions used in this PDF

Name of basis function is **RooFormulaVar** expression
@0 is convolution variable
@1..@n are basis function parameters

Return code assign unique integer code to each declared basis

Class **RooConvolutedPdf** – Coefficient implementation

- Method **coefficient()** implements all coefficient values

Requested index is one of the basis function codes returned by **declareBasis()**

```
Double_t RooBMixDecay::coefficient(Int_t basisIndex) const
{
  if (basisIndex==_basisExp) {
    return (1 - _tagFlav*_delMistag) ;
  }

  if (basisIndex==_basisCos) {
    return _mixState*(1-2*_mistag) ;
  }
  return 0 ;
}
```

- **At this point class is complete and functional**

Class **RooConvolutedPdf** – Analytical integrals

- You can optionally advertise and implement analytical integrals for your coefficient functions
  - Interface similar to analytical integrals in RooAbsReal

- Advertising coefficient integrals
  - Method identical to **RooAbsReal::getAnalyticalIntegral()**, just the name is different

```
Int_t getCoefAnalyticalIntegral(RooArgSet& allVars,
                                RooArgSet& analVars) const ;
```

- Implementing coefficient integrals
  - Method similar to **RooAbsReal::analyticalIntegral()**
  - One extra argument to identify the coefficient in question

```
Double_t coefAnalyticalIntegral(Int_t coef,
                                Int_t code) const ;
```

Class **RooConvolutedPdf** – Internal generator implementation

- You can optionally advertise and implement an internal generator for the *unconvoluted* PDF function
  - Methods identical to regular PDF generator implementation
- An internal generator will greatly accelarate toyMC generation from a convoluted PDF
  - If both physics PDF and resolution model provide internal generators, then events can be generated as

$$x_{P \otimes R} = x_P + x_R$$

    i.e. no convolutions integrals need to be evaluated

  - Only works with internal generator implementations because both $\boldsymbol{x_P}$ and $\boldsymbol{x_R}$ must be generated on an unbound domain for this technique to work
    - Accept reject sample doesn't work on unbound domains

Writing a resolution model – physics/resolution factorization

- Physics model and resolution model are implemented separately in RooFit
  - Factorization achieved via a common set 'basis functions' f_k

Implements $f_i(dt,...) \otimes R(dt,...)$
Also a PDF by itself

RooResolutionModel

$$P(dt,...) = \sum_k \overbrace{c_k(...)\left(f_k(dt,...) \otimes R(dt,...)\right)}$$

RooConvolutedPdf (physics model)

- Implements c_k
- Declares list of f_k needed

Writing a resolution model PDF – class **RooResolutionModel**

- Class declaration

```
class RooGaussModel : public RooResolutionModel {
public:
```

Resolution model classes inherit from **RooResolutionModel** instead of **RooAbsPdf**

```
  RooGaussModel(const RooBMixDecay& other, const char* name=0);
  virtual TObject* clone(const char* newname) const ;
  virtual ~RooGaussModel();
```

Method **basisCode()** advertises supported basis functions

```
  virtual Int_t basisCode(const char* name) const = 0 ;
  virtual Double_t evaluate() const ;

protected:
  …
  ClassDef(Roo
};
```

evaluate() returns *regular or convoluted* PDF depending on internal state

Class **RooResolutionModel** – Advertising basis functions

- Function **basisCode()** assigns unique integer code to each supported basis function

```
Int_t RooGaussModel::basisCode(const char* name) const
{
 if (!TString("exp(-@0/@1)").CompareTo(name)) return 1 ;
 if (!TString("exp(@0/@1)").CompareTo(name)) return 2 ;
 if (!TString("exp(-abs(@0)/@1)").CompareTo(name)) return 3 ;
 if (!TString("exp(-@0/@1)*sin(@0*@2)").CompareTo(name)) return 4 ;
 if (!TString("exp(@0/@1)*sin(@0*@2)").CompareTo(name)) return 5 ;
 if (!TString("exp(-abs(@0)/@1)*sin(@0*@2)").CompareTo(name)) return 6;
 if (!TString("exp(-@0/@1)*cos(@0*@2)").CompareTo(name)) return 7 ;
 if (!TString("exp(@0/@1)*cos(@0*@2)").CompareTo(name)) return 8 ;
 if (!TString("exp(-abs(@0)/@1)*cos(@0*@2)").CompareTo(name)) return 9;
 return 0 ;
}
```

Return 0 if basis function is not supported

Class RooResolutionModel – Implementing evaluate()

- evaluate() returns both convoluted and unconvoluted PDF value

currentBasisCode() returns the ID of the basis function we're convoluted with.
If zero, not convoluted is requested

```
Double_t RooGaussModel::evaluate() co
{
  Int_t code = currentBasisCode() ;

  if (code==0) {
    // return unconvoluted PDF value ;
  }

  if (code==1) {
    // Return PDF convoluted with basis function #1

    // Retrieve basis function paramater value
    Double_t tau = basis().getParameter(1))->getVal() ;
  }
}
```

Class **RooResolutionModel** – Implementing **evaluate()**

- **evaluate()** returns both convoluted and unconvoluted PDF value

```
Double_t RooGaussModel::evaluate() const
{
  Int_t code = currentBasisCode() ;

                                 uted PDF value ;

  if (code==1)
    // Return PD   nvoluted with

    // Retrieve basis function param   ter value
    Double_t tau = basis().getParameter(1))->getVal() ;
  }
}
```

basis() returns a reference to the **RooFormulaVar** representing the current basis function

getParameter(n) returns a **RooAbsReal** reference to the n^{th} parameter of the **RooFormulaVar**

Class **RooResolutionModel** – Analytical integrals

- Advertising and implementing analytical integrals works the same way as in RooAbsPdf

Advertisement and implementation should reflect the 'current' convolution indicated by **currentBasisCode()**

```
Int_t RooGaussModel::
      getAnalyticalIntegral(Ro      t& allVars,
                                   gSet& analVars) const
{
  switch(currentBasisCode()) {
  // Analytical integration capability of raw PDF
  case 0:
    if (matchArgs(allVars,analVars,convVar())) return 1 ;
    break ;

  // Analytical integration capability of convoluted PDF
  case 1:
  if (matchArgs(allVars,analVars,convVar())) return 1 ;
    break ;
  }
}
```

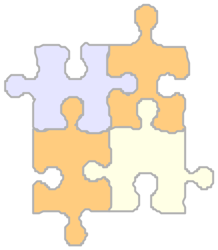
Class **RooResolutionModel** – Internal generator implementation

- You can optionally advertise and implement an internal generator for the *unconvoluted* resolution model
  - Methods identical to regular PDF generator implementation

Class **`RooAbsGoodnessOfFit`** – Goodness of fit

- No time left to write this section… (sorry!)

Debugging



ROOT and gdb/dbx

Finding memory leaks

Tracing function evaluation

Checking integrals & generators

Profiling

Using the system debugger

- Compiled applications linked with RooFit
  - Just use '**gdb/dbx <executable>**'
- Interactive ROOT
  - You can use gdb/dbx to debug your compiled RooFit class
  - Trick: attach debugger to already running ROOT process
    1. Start interactive ROOT the usual way
    2. In a separate shell on the same host
       attach gdb/dbx to the running ROOT session
    3. Resume running of ROOT
       gdb> continue
    4. Execute the code you want to test

```
#!/bin/sh
line=`ps -wwfu $USER | grep root.exe | grep -v grep | tail -1`
if [ "$line" = "" ] ; then
 echo "No ROOT session running"
 exit 1
fi
set $line
exec gdb $8 $2
```

Finding memory leaks

- **`RooTrace`** utility keeps track of RooFit object allocation

```
RooTrace::active(kTRUE)

RooRealVar x("x","x",-10,10) ;
RooGaussian g("g","g",x,RooConst(0),RooConst(1)) ;

RooTrace::dump(cout);
List of RooFit objects allocated while trace active:
00086b7118 :           RooRealVar - x
00086aa178 :           RooArgList - RooRealVar Constants Database
00086b7658 :          RooConstVar - 0.000000
00086b7b08 :          RooConstVar - 1.000000
00086bc3e8 :          RooGaussian - g
```

Finding memory leaks

- You can do incremental leak searches

```
RooTrace::active(kTRUE)

RooRealVar x("x","x",-10,10) ;
RooGaussian g("g","g",x,RooConst(0),RooConst(1)) ;

RooTrace::mark() ; // mark all objects created sofar

RooGaussian g2("g2","g2",x,RooConst(2),RooConst(1)) ;

// Dump only objects created since last mark
RooTrace::dump(cout,kTRUE);
List of RooFit objects allocated while trace active:
00086c8f50 :          RooConstVar - 2.000000
00086c9400 :          RooGaussian - g2
5 marked objects suppressed
```

Tracing function evaluation

- When you have many instances of a single class it can be more useful to trace function evaluation with printed messages than via debugger
  - Debugger breakpoint will stop in every instance of your class even if you only want to examine a single instance
- RooFit provides system-wide tracing techniques
  - **`RooAbsArg::setVerboseDirty(kTRUE)`**
    - Track lazy evaluation logic of RooAbsArg classes
    - May help to understand why your evaluate() doesn't get called
  - **`RooAbsArg::setVerboseEval(Int_t level)`**
    - Level 0 – No messages
    - Level 1 – Print one-line message each time a normalization integral is recalculated
    - Level 2 – Print one-line message each time a PDF is recalculated
    - Level 3 – Provide details of convolution integral recalculations

Tracing function evaluation

- And object-specific tracing techniques
  - **`pdf->setTraceCounter(Int_t n, Bool_t recursive)`**
  - Prints one-lines messages for the next **`n`** times **`pdf`** is evaluated
  - If recursive option is set, trace counter is also set for all component PDFs of **`pdf`**
  - Useful in fitting/likelihood calculations where is single likelihood evaluation can trigger thousands of PDF evaluations

Checking analytical integrals and internal generators

- Function integrals and PDF event generators both have a numerical backup solution
  - You can use those as a cross check to validate your function/PDF-specific implementation
- Integrals
  - **`RooAbsReal::forceNumInt(kTRUE)`** will disable the use of any advertised analytical integrals
- Generators
  - **`RooAbsPdf::forceNumGen(kTRUE)`** will disable the use of any advertised internal PDF generator methods

Profiling

- To run the profiler you must build your test application as a standalone executable
  - compile & link with **–pg** flag

```
#include "TROOT.h"
#include "TApplication.h"

// Instantiate ROOT system
TROOT root("root", "root");
int main(int argc, char **argv)
{
  // Instantiate graphics event handler
  TApplication app("TAppTest",&argc,argv) ;

  // User code goes here
}
```

  - *You cannot have any RooFit classes as global variables*
    - Prior instantiation of TROOT needed, but cannot be guaranteed
  - Place your driver executable in the **RooFitModels** directory and list it as a binary target in the **GNUMakefile**

Outlook

- New goodness-of-fit calculation classes will be introduced soon (~1 week)
  - Likelihood and ChiSquare as examples.
  - Complete function optimization support for likelihood fitting now generically available for all goodness of fits
  - Built-in support for handling RooSimultaneous PDFs
  - Support for parallel execution on multi-CPU hosts
    - No support from user code needed except prescription to merge partial results (Default implementation adds partial results)