# Computer Vision using Ruby and libJIT

WEDEKIND, Jan



**Published version**

WEDEKIND, Jan (2009). Computer Vision using Ruby and libJIT. In: RubyConf 2009, San Francisco, California.

Hornets Eye

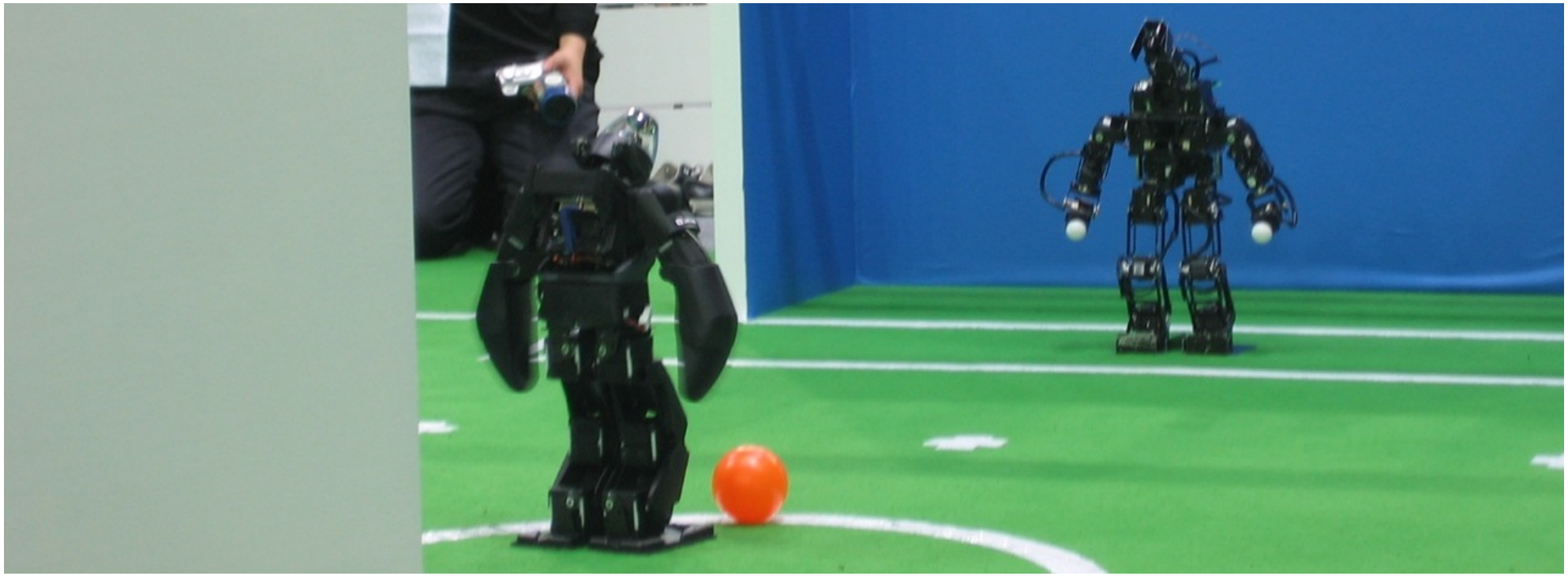
## RubyConf 2009

# Computer Vision using Ruby and libJIT


**Jan Wedekind**

**Thu Nov 19 13:15:00 PST 2009**

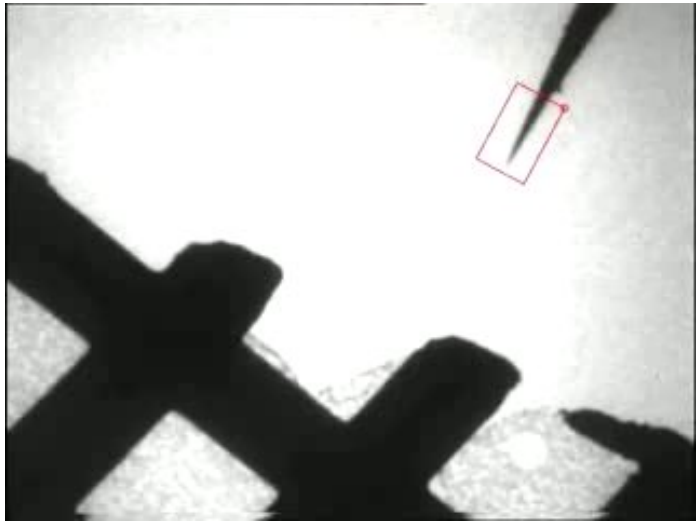
**Embassy Suites San Francisco Airport, Room 1**

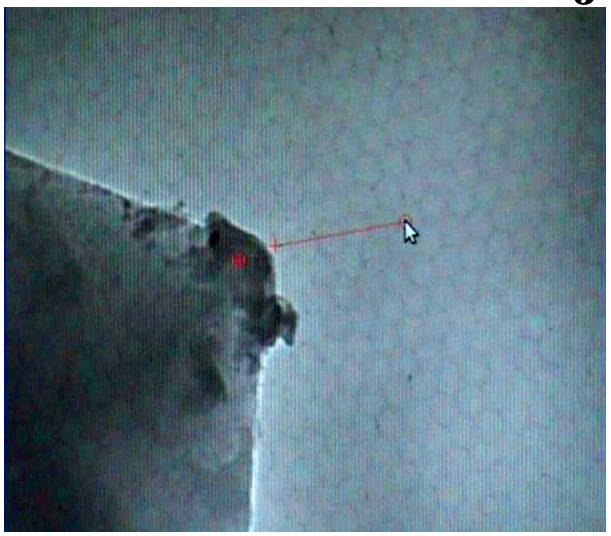


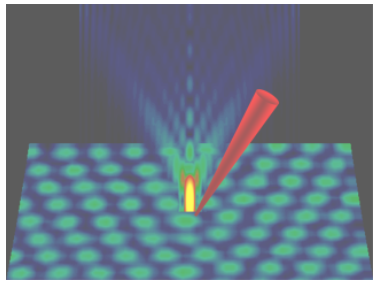
http://www.flickr.com/photos/schoschie/171544759/

# Background

## EPSRC Nanorobotics Project







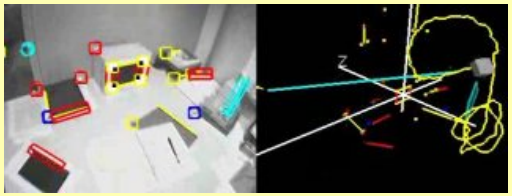
EPSRC


http://vision.eng.shu.ac.uk/mmvlwiki/index.php/Nanorobotics

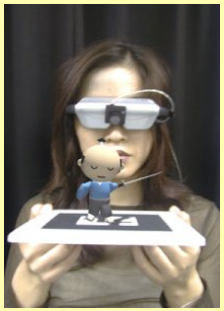
http://nano.group.shef.ac.uk/

Hornets Eye

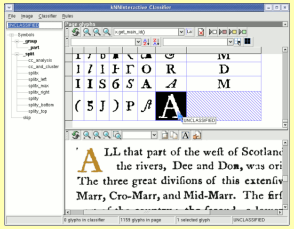
# Applications of Computer Vision



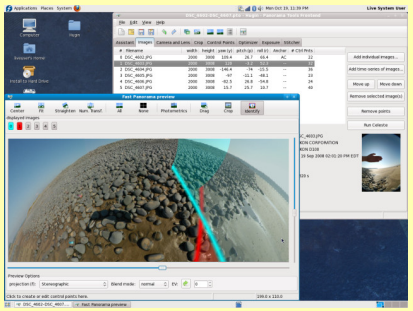
Visual Navigation



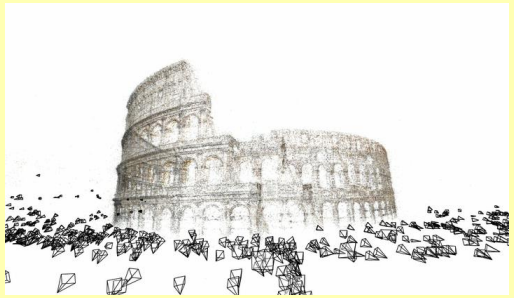
Augmented Reality



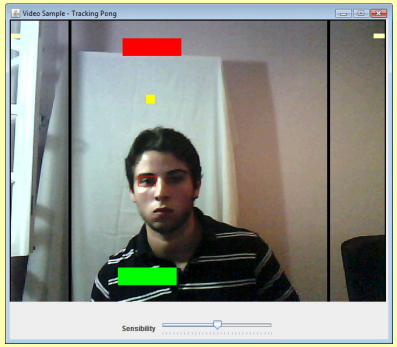
Optical Character Recognition



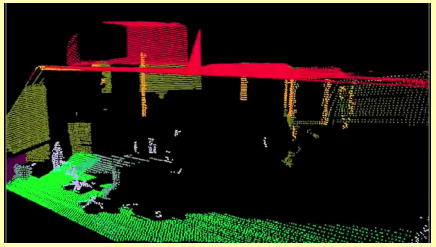
Panorama Stitching



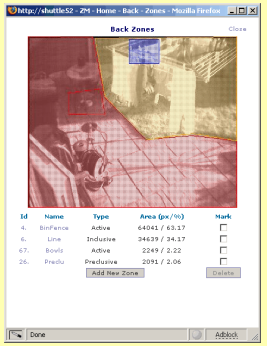
3D Reconstruction



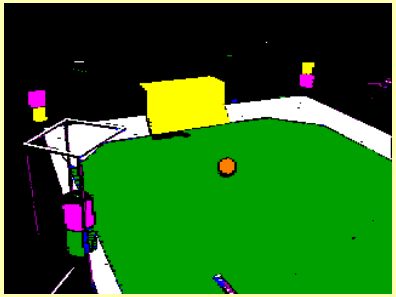
Games



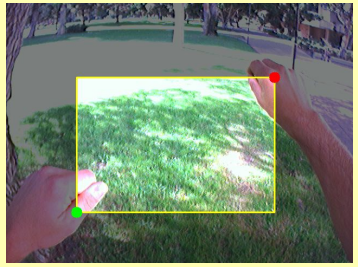
3D Object Recognition



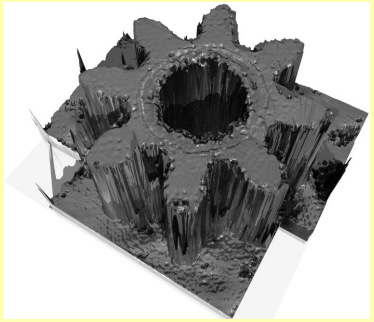
Surveillance



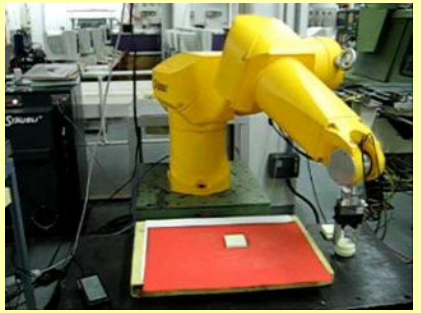
Segmentation



Human Computer Interfaces



Inspection



Automation


# The Array Challenge

## Computer Vision means Array Operations

### C/C++

```c
#include <stdlib.h>
#define SIZE 10000000
int main(void)
{
  int i, *arr = (int *)
    malloc( SIZE *
            sizeof(int) );
  for ( i = 0; i < SIZE; i++ )
    arr[ i ] = i;
  free( arr );
  return 0;
}
```

**gcc 4.2.4 0.06s**

### Ruby

```ruby
SIZE = 10000000
arr = ( 0 ... SIZE ).
  collect { |i| i }
```

**ruby 1.8.6 76.3s**

**ruby 1.9.1 1.8s**

Intel® Core™2 CPU T5600 @ 1.83GHz

Linux 2.6.24-24-generic SMP i686 GNU/Linux

# Maybe we shouldn't use Ruby here?


http://www.imdb.com/title/tt0343818/


# Expressiveness (multi-dimensional '+')

## C++ and Boost::MultiArray

```
#include <boost/multi_array.hpp> // 3726 lines of code
#include <iostream>
using namespace boost;
template< typename T >
T &multi_plus( T &a, const T &b, const T &c )
{
  a = b + c;
  return a;
}
template< template< typename, size_t, typename > class Arr,
          typename Alloc, typename T, size_t N >
detail::multi_array::sub_array< T, N > multi_plus
( detail::multi_array::sub_array< T, N > a,
  const Arr< T, N, Alloc > &b, const Arr< T, N, Alloc > &c )
{
  typename Arr< T, N, Alloc >::const_iterator j = b.begin();
  typename Arr< T, N, Alloc >::const_iterator k = c.begin();
  for ( typename detail::multi_array::sub_array< T, N >::
          iterator i = a.begin(); i != a.end(); i++, j++, k++ )
    multi_plus( *i, *j, *k );
  return a;
}
template< template< typename, size_t, typename > class Arr,
          typename Alloc, typename T, size_t N >
Arr< T, N, Alloc > &multi_plus
( Arr< T, N, Alloc > &a,
  const Arr< T, N, Alloc > &b, const Arr< T, N, Alloc > &c )
{
  typename Arr< T, N, Alloc >::const_iterator j = b.begin();
  typename Arr< T, N, Alloc >::const_iterator k = c.begin();
  for ( typename Arr< T, N, Alloc >::
          iterator i = a.begin(); i != a.end(); i++, j++, k++ )
    multi_plus( *i, *j, *k );
  return a;
}
```

```
template < template< typename, size_t, typename > class Arr,
           typename Alloc, typename T, size_t N >
multi_array< T, N > operator+
( const Arr< T, N, Alloc > &a,
  const Arr< T, N, Alloc > &b )
{
  array< size_t, N > shape;
  std::copy( a.shape(), a.shape() + N, shape.begin() );
  multi_array< T, N > retVal( shape );
  multi_plus( retVal, a, b );
  return retVal;
};
int main(void)
{
  multi_array< int, 2 > a( extents[ 2 ][ 2 ] );
  a[0][0] = 1; a[0][1] = 2; a[1][0] = 3; a[1][1] = 4;
  multi_array< int, 2 > b( extents[ 2 ][ 2 ] );
  b[0][0] = 5; b[0][1] = 4; b[1][0] = 3; b[1][1] = 2;
  multi_array< int, 2 > r( a + b );
  std::cout << "[ [ " << r[0][0] << ", " << r[0][1]
            << " ], [ " << r[1][0] << ", " << r[1][1]
            << " ] ]" << std::endl;
  // [ [ 6, 6 ], [ 6, 6 ] ]
  return 0;
}
```

Hornets Eye

# Expressiveness (multi-dimensional '+')

## Ruby and Standard Library

```ruby
class Array
  def +( other )
    zip( other ).collect { |x,y| x + y }
  end
end
a = [ [ 1, 2 ], [ 3, 4 ] ]
b = [ [ 5, 4 ], [ 3, 2 ] ]
puts ( a + b ).inspect
# [ [ 6, 6 ], [ 6, 6 ] ]
```

straightforward!

# Implementation

## Uniform Arrays

[  ,  ,  ,  ,  ,  ,  , ... ]

Also see: NArray

# Implementation

## Malloc Objects

```
m = Malloc.new 10

m.write '0123456789'

# "0123456789"

m.read 5

# "01234"

( m + 2 ).read 5

# "23456"
```

# Implementation

## Using 'Array#pack' and 'String#unpack'

```ruby
class INT
  def initialize( v = 0 )
    @malloc = Malloc.new 4
    set v
  end
  def inspect
    "#{ self.class.inspect }(#{ get })"
  end
  def set( v = 0 )
    @malloc.write [ v ].pack( 'i' )
    v
  end
  def get
    @malloc.read( 4 ).unpack( 'i' )[ 0 ]
  end
end
```

```ruby
i = INT.new 3
# INT(3)
i.set 5
# 5
i
# INT(5)
i.get
# 5
```

# Implementation

## Type System: Generic Native Scalar

```
class INT_
  class << self
    attr_accessor :bits
    attr_accessor :signed
  end
  # ...
end
SIGNED   = true
UNSIGNED = false
def INT( bits, signed )
  retval = Class.new INT_
  retval.bits = bits
  retval.signed = signed
  retval
end
```

```
USINT = INT 16, UNSIGNED
# USINT
u = USINT.new 3
# USINT(3)
v = USINT.new u.malloc
# USINT(3)
```

Hornets Eye

# Implementation

## Type System: Native Arrays

```
class Sequence_
  class << self
    attr_accessor :elem, :num,
                  :stride
  end
  # ...
  def sel( i )
    elem.new @malloc + i *
             elem.bytes * stride
  end
  def []( i )
    sel( i ).get
  end
  def []=( i, v )
    sel( i ).set v
  end
end
```

```
SINT = INT 16, SIGNED
# SINT
s = Sequence( SINT, 8 ).new.fill!
# Sequence(SINT,8):
# [ 0, 0, 0, 0, 0, 0, 0, 0 ]
s[ 3 ] = 5
# 5
s
# Sequence(SINT,8):
# [ 0, 0, 0, 5, 0, 0, 0, 0 ]
s[ 3 ]
# 5
s.sel 3
# SINT(5)
```


# Implementation

## Type System: Recursive Arrays

```
M = Sequence( Sequence( INT( 32, SIGNED ), 3 ), 2 )
# MultiArray.int(3,2)
m = M.new.fill! 1
# MultiArray.int(3,2):
# [ [ 1, 1, 1 ],
#   [ 1, 1, 1 ] ]
m[ 1 ]
# Sequence.int(3):
# [ 1, 1, 1 ]
m[ 2, 1 ]
# 1
m[ 1 ][ 2 ] = 0
# 0
m[ 1 .. 2, 0 .. 1 ]
# MultiArray.int(2,2):
# [ [ 1, 1 ],
#   [ 1, 0 ] ]
```

Hornets Eye

# Array Operations


# Implementation

## Array Operations: Scalar Operations

```
module RubyScalar
  def op( *args, &action )
    instance_exec *args, &action
    self
  end
  def -@
    self.class.new.op( get ) { |x| set -x }
  end
  # ...
end
class INT_
  include RubyScalar
end
```

```
i = SINT.new 3
# SINT(3)
-i
# SINT(-3)
```


# Implementation

## Array Operations: Element-Wise Array Operations

```
module RubySequence
  def op( *args, &action )
    for i in 0 ... num
      subargs = args.collect do |v|
        v.is_a?( Sequence_ ) ? v[ i ] : v
      end
      sel( i ).op *subargs, &action
    end
    self
  end
  def -@
    self.class.new.op( get ) { |x| set -x }
  end
end
class Sequence_
  include RubySequence
end
```

```
S = Sequence( INT, 3 )
# Sequence.int(3)
s = S.new.indgen!
# Sequence.int(3):
# [ 0, 1, 2 ]
-s
# Sequence.int(3):
# [ 0, -1, -2 ]
```

Hornets Eye

# How to speed-up things?

Hornets Eye

# Implementation

## Reflection in Ruby: Example

```ruby
class Const
  attr_accessor :inspect
  alias_method :to_s, :inspect
  def initialize( s )
    @inspect = s.to_s
  end
  def method_missing( name, *args )
    str = "#{ self }.#{ name }"
    unless args.empty?
      str += "( #{args.join ', '} )"
    end
    Const.new str
  end
  def coerce( y )
    return Const.new( y ), self
  end
end
```

```ruby
a = Const.new 'a'
# a
b = Const.new 'b'
# b
-a
# a.-@
a + b
# a.+( b )
a[ 2 ]
# a[]( 2 )
2 * a
# 2.*( a )
2 * a + b
# 2.*( a ).+( b )
2 * ( a + b )
# 2.*( a.+( b ) )
```

# Implementation

## Reflection in Ruby: Limitations

```
a or b
# a

a < b ? a : b
# a

b = a
# a

if a > b
  a -= b
end
# a.-( b )

begin
  a += 1
end until a > b
a
# a.+( 1 )
```

```
b and a
# a

a > b ? a : b
# a

x = a
# a

a - b
#
#
# a.-( b )

b = a + 1
#
#
#
# a.+( 1 )
```

# Implementation

## JIT-Compilation: Scalar Operation I/II

```
module JITScalar
  def op( *args, &action )
    if ( [ self ] + args ).all? { |arg| arg.jit_support? }
      JITFunction.jit( self, *args ) do |f,_self,*_args|
        _self.op *_args, &action
      end
      self
    else
      super *args, &action
    end
  end
end
class INT_
  include JITScalar
end
```

'JITFunction.jit': cache, compile, and execute

# Implementation

## JIT-Compilation: Scalar Operation II/II

```
i = INT.new 3
# INT(3)
i.class.new.op( i.get ) do |x|
  puts "self = #{self}"
  puts "x    = #{x}"
  puts
  set -x
end
# self = INT(*i1)
# x    = i2

# INT(-3)
```

```
function -@( i1:  ptr,
             i2:  int ):  void
  i3 = -i2
  *i1 = i3
```

machine code generated by libJIT/ DotGNU

http://freshmeat.net/projects/libjit/

Also see: ruby-libjit

Hornets Eye

# Implementation

## JIT-Compilation: Array Operation I/V

```
module JITSequence
  def op( *args, &action )
    if ( [ self ] + args ).all? { |arg| arg.jit_support? }
      JITFunction.jit( self, *args ) do |f,_self,*_args|
        _self.op *_args, &action
      end
      self
    elsif is_jit?
      f = malloc.f
      r = JITTerm.value f, JITType::PTR, malloc
      s = stride * elem.bytes
      rend = r + s * num
```

# Implementation

## JIT-Compilation: Array Operation II/V

```
extract, increment = [], []
args.each do |arg|
  if arg.is_a? Sequence_
    ptr = JITTerm.value f, JITType::PTR, arg.malloc
    astride = arg.stride * arg.elem.bytes
    extract.push proc { arg.elem.new( ptr ).get }
    increment.push proc { ptr.set ptr + astride }
  else
    extract.push proc { arg }
  end
end
```

# Implementation

## JIT-Compilation: Array Operation III/V

```
      f.until( proc { r == rend } ) do
        _subargs = extract.collect { |i| i.call }
        elem.new( r ).op *_subargs, &action
        increment.each { |i| i.call }
        r.set r + s
      end
    else
      super *args, &action
    end
  end
end
class Sequence_
  include JITSequence
end
```

Also cumbersome but much more generic!

# Implementation

## JIT-Compilation: Array Operation IV/V

```
s = Sequence( INT, 3 ).new.indgen!
# Sequence(INT,3):
# [ 0, 1, 2 ]
s.class.new.op( s.get ) do |x|
  puts "self = #{self}"
  puts "x    = #{x}"
  puts
  set -x
end
# self = INT(*i7)
# x    = i13

# Sequence(INT,3):
# [ 0, -1, -2 ]
```

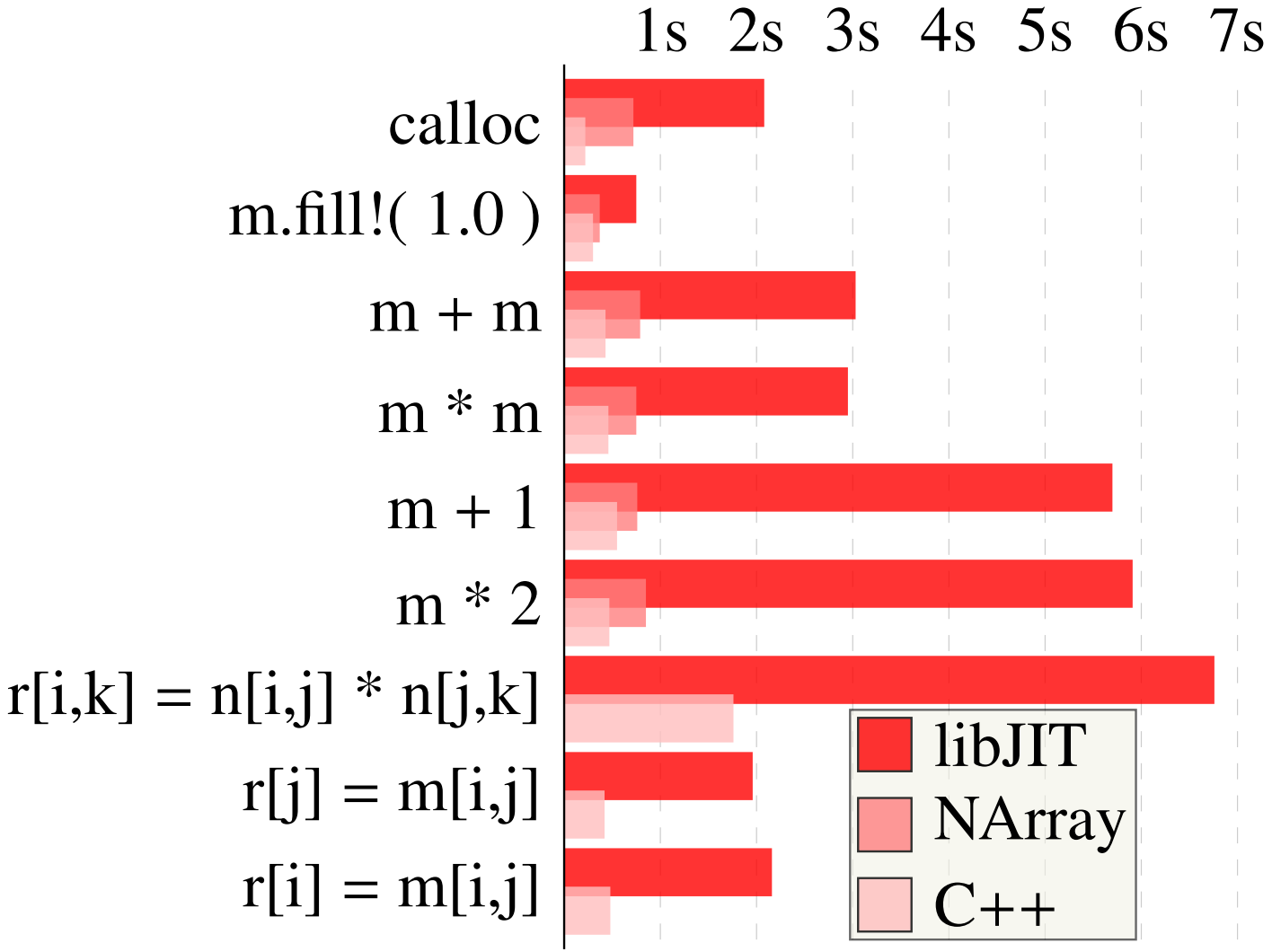
# Implementation

## JIT-Compilation: Array Operation V/V

```
function -@( i1:  int, i2:  int, i3:  ptr,
             i4:  int, i5:  int, i6:  ptr ):  void
  i7 = i3
  i8 = i2 * 4
  i9 = i8 * i1
  i10 = i7 + i9
  i11 = i6
  i12 = i5 * 4
L0:
  if i7 == i10 then goto L1
  i13 = *i11
    i14 = -i13
    *i7 = i14
  i11 = i11 + i12
  i7 = i7 + i8
  goto L0
L1:
```

# Implementation

## JIT Results




Intel® Core™2 CPU T5600 @ 1.83GHz

Linux 2.6.24-24-generic SMP i686 GNU/Linux

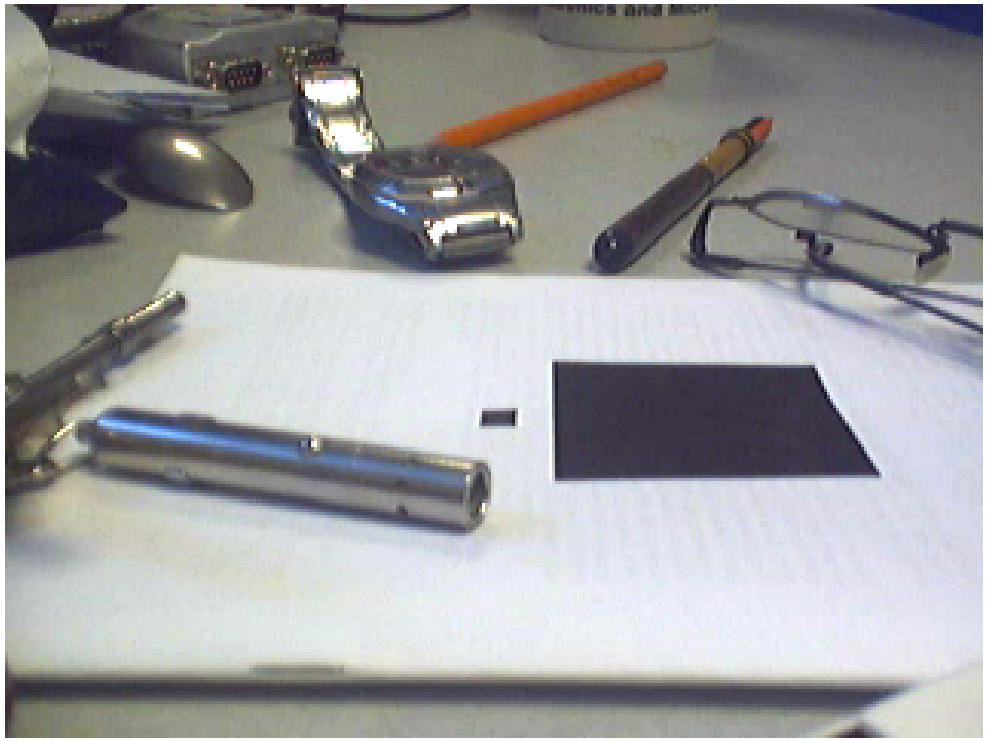
⇒ future work: prefill cache with GCC code (use RubyInline?)

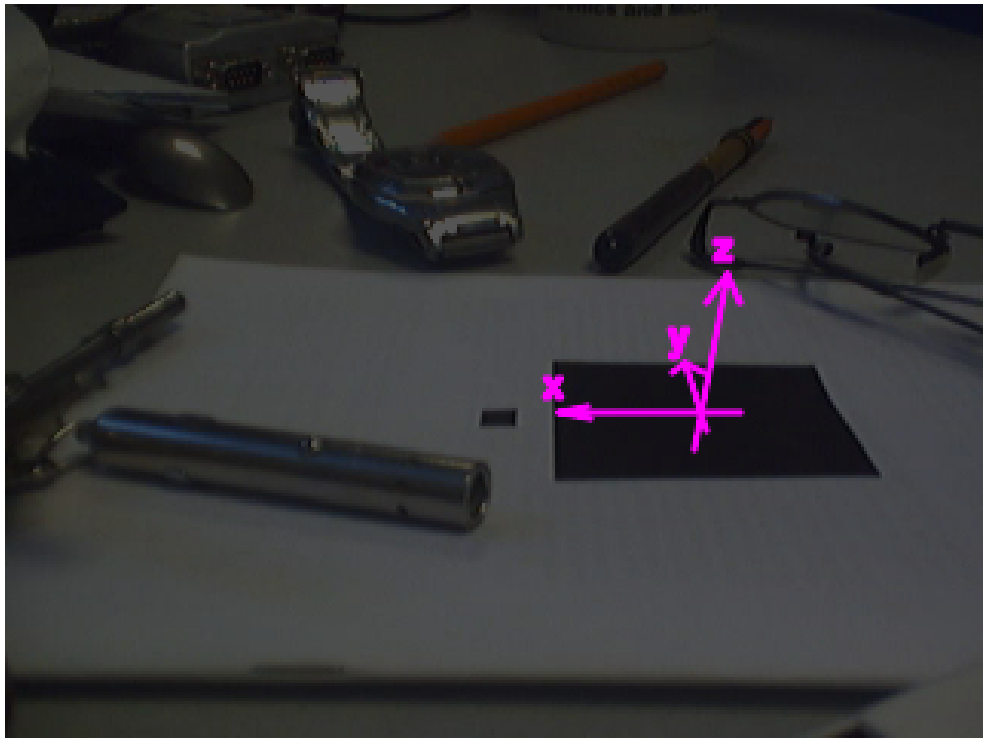
Hornets Eye

# Augmented Reality Example

## Problem: 3D recognition of planar object

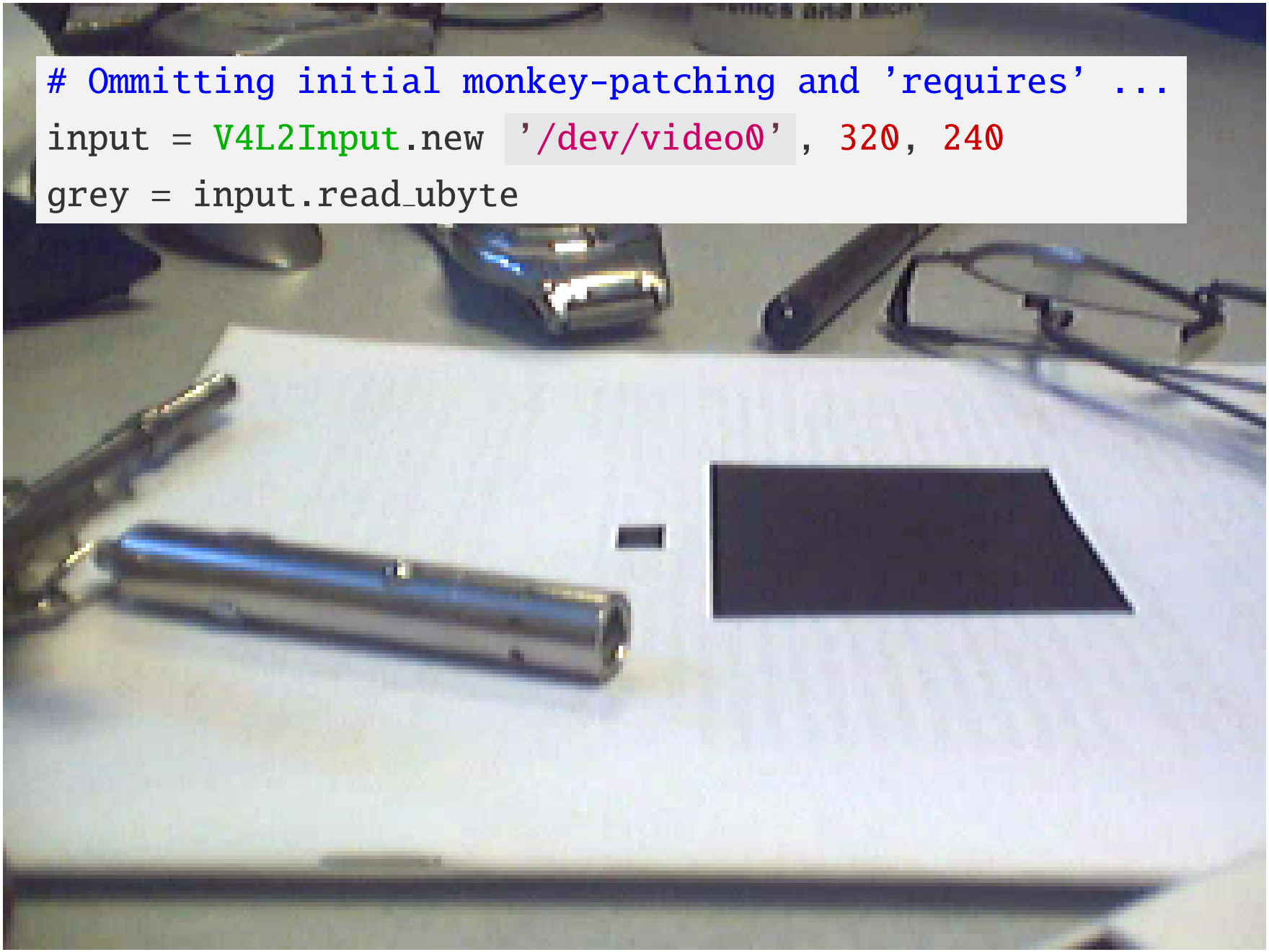
How to get from here . . . . . to here?





# Augmented Reality Example

## Capture Image



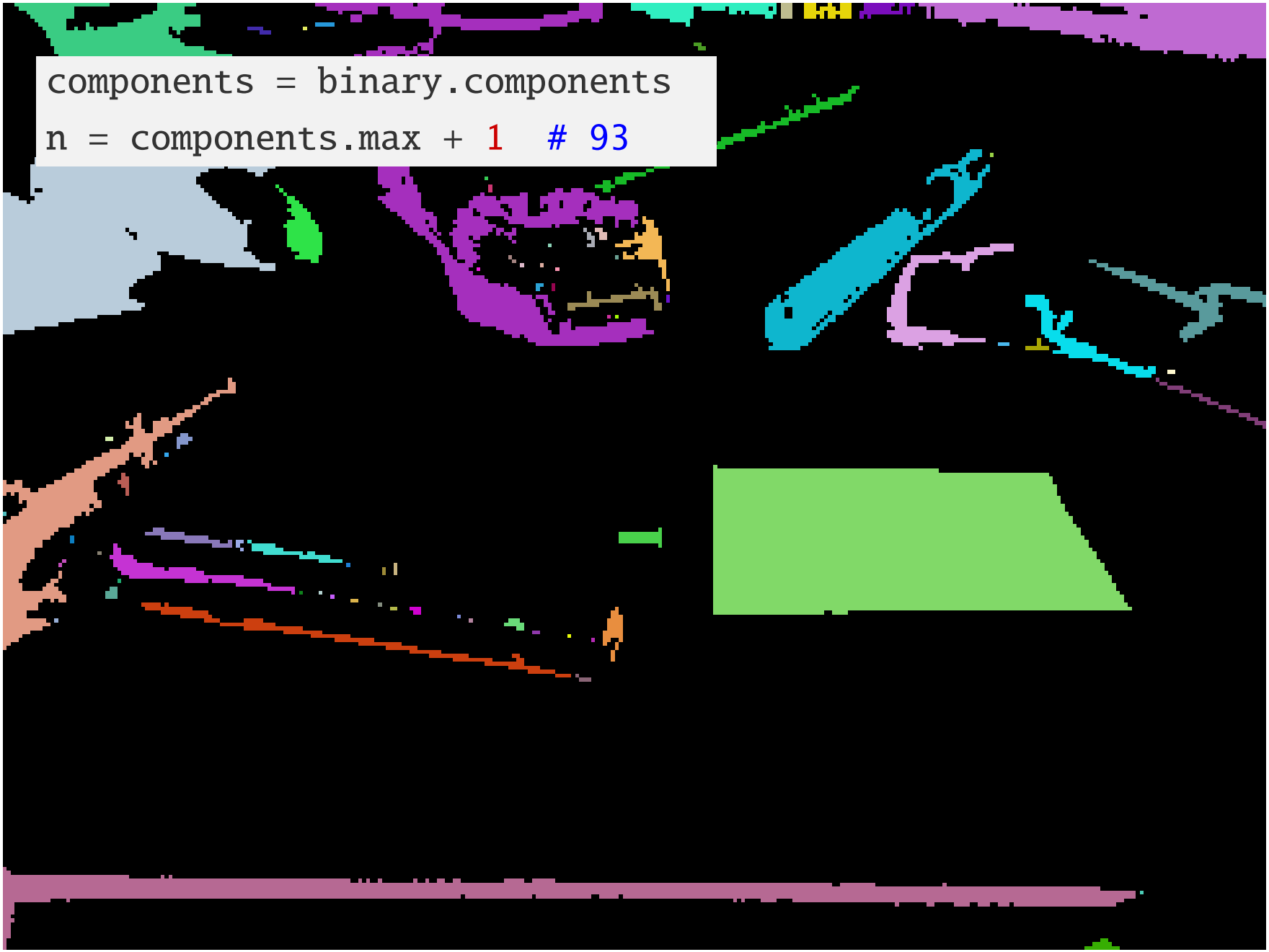

```
# Ommitting initial monkey-patching and 'requires' ...
input = V4L2Input.new '/dev/video0', 320, 240
grey = input.read_ubyte
```

# Augmented Reality Example

## Threshold Image

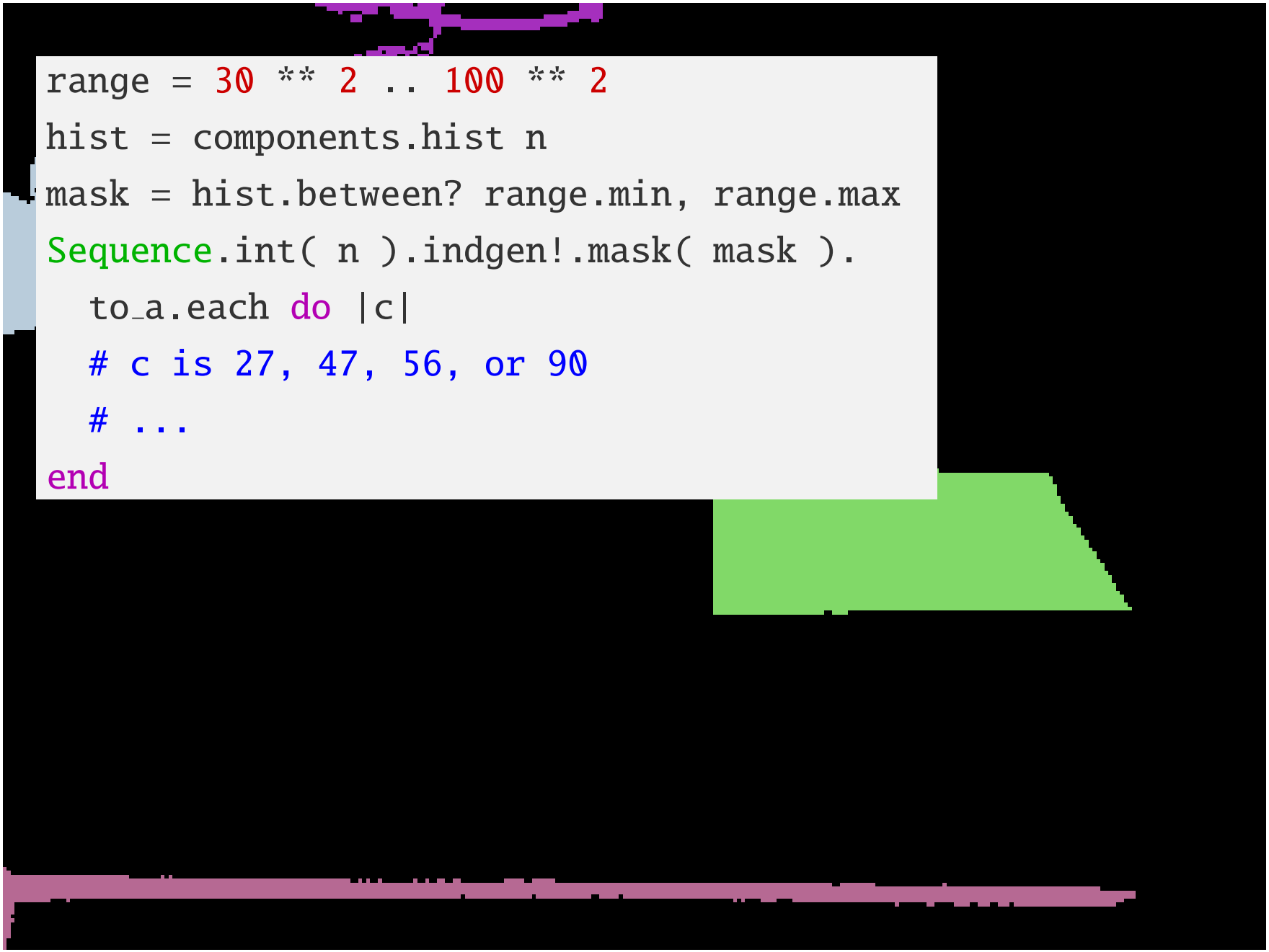
# Augmented Reality Example

## Connected Component Analysis



# Augmented Reality Example

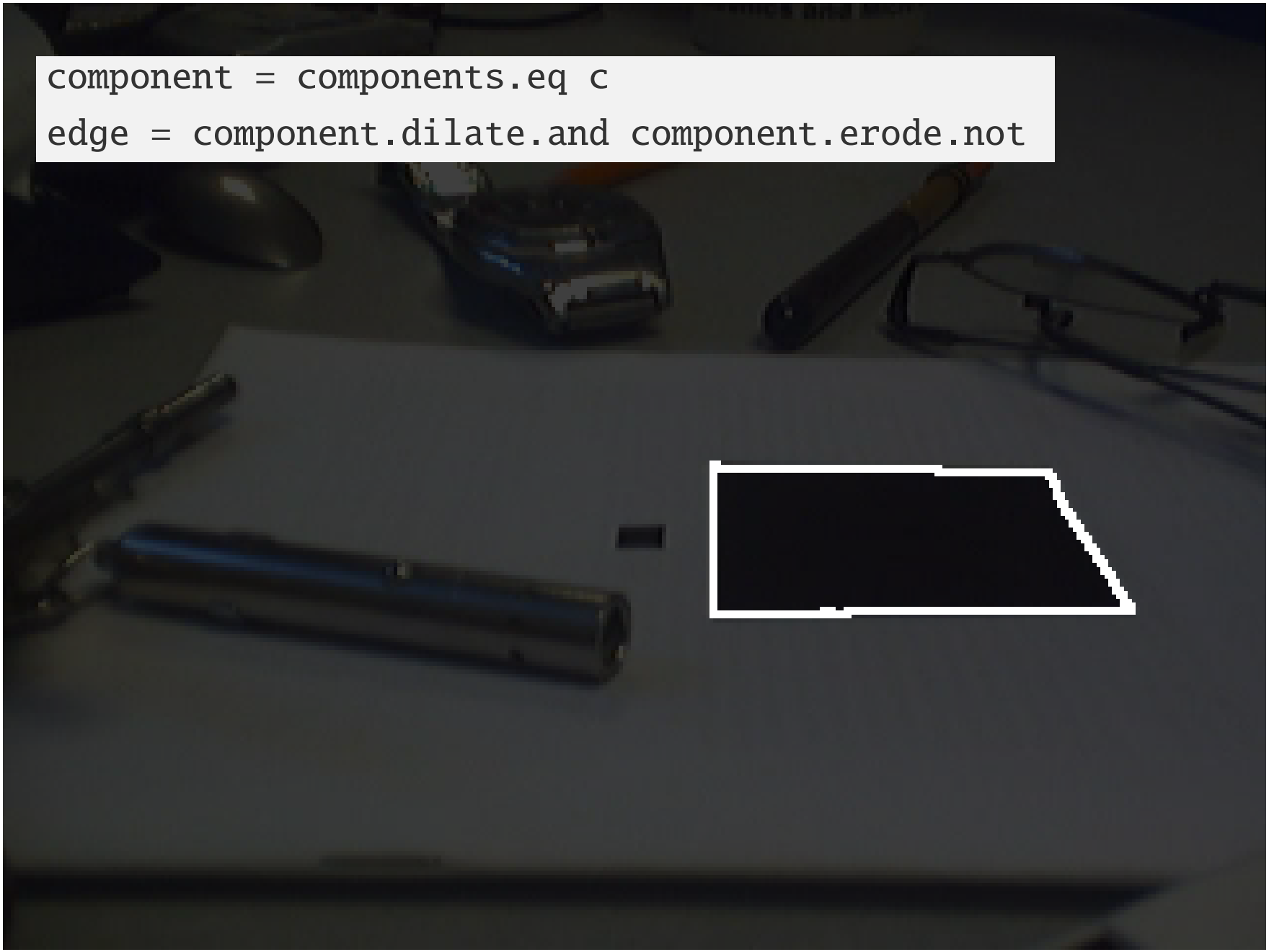
## Impose Size Constraints



```
range = 30 ** 2 .. 100 ** 2
hist = components.hist n
mask = hist.between? range.min, range.max
Sequence.int( n ).indgen!.mask( mask ).
  to_a.each do |c|
  # c is 27, 47, 56, or 90
  # ...
end
```

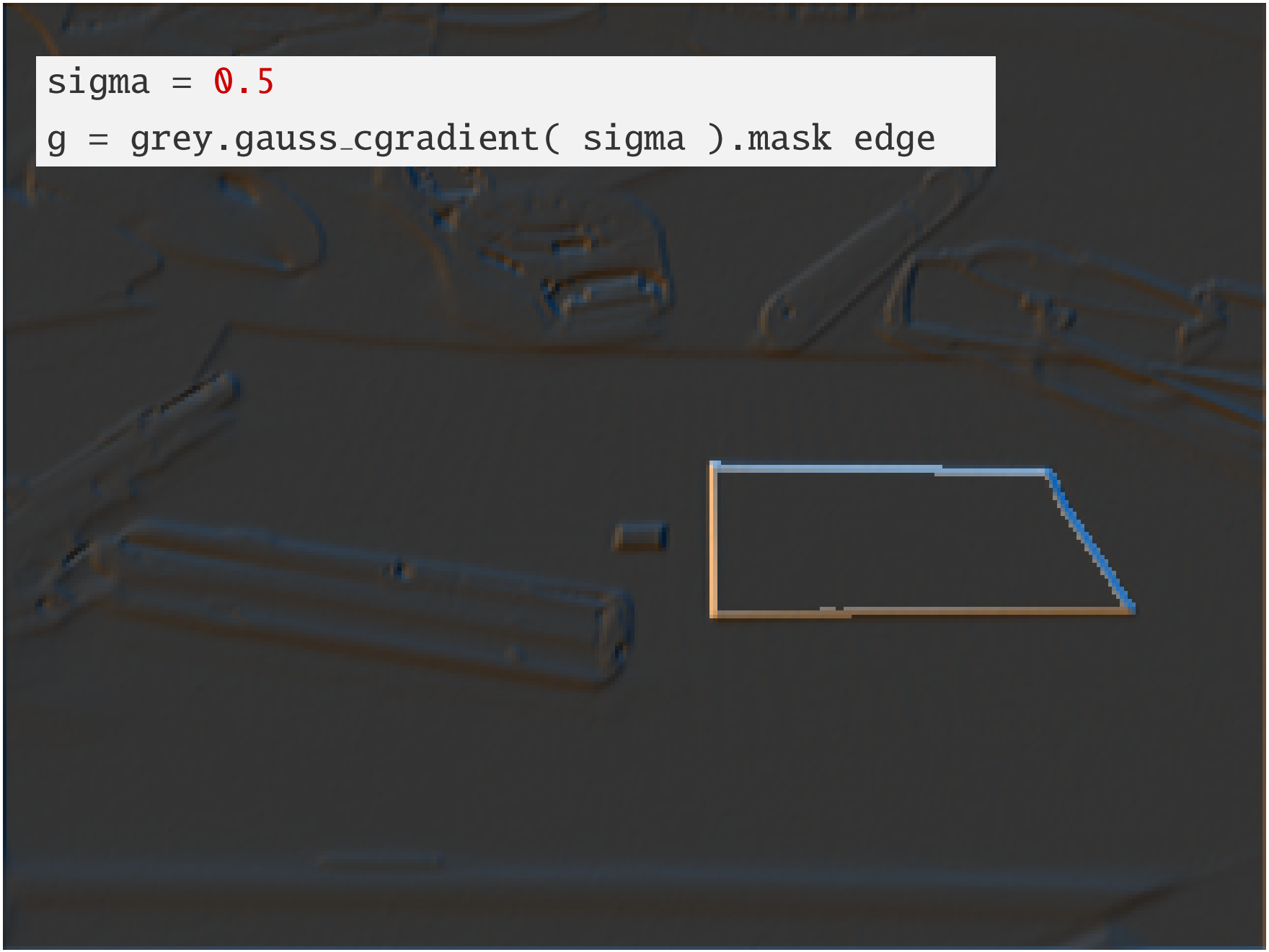
# Augmented Reality Example

## Extract Edge of Component



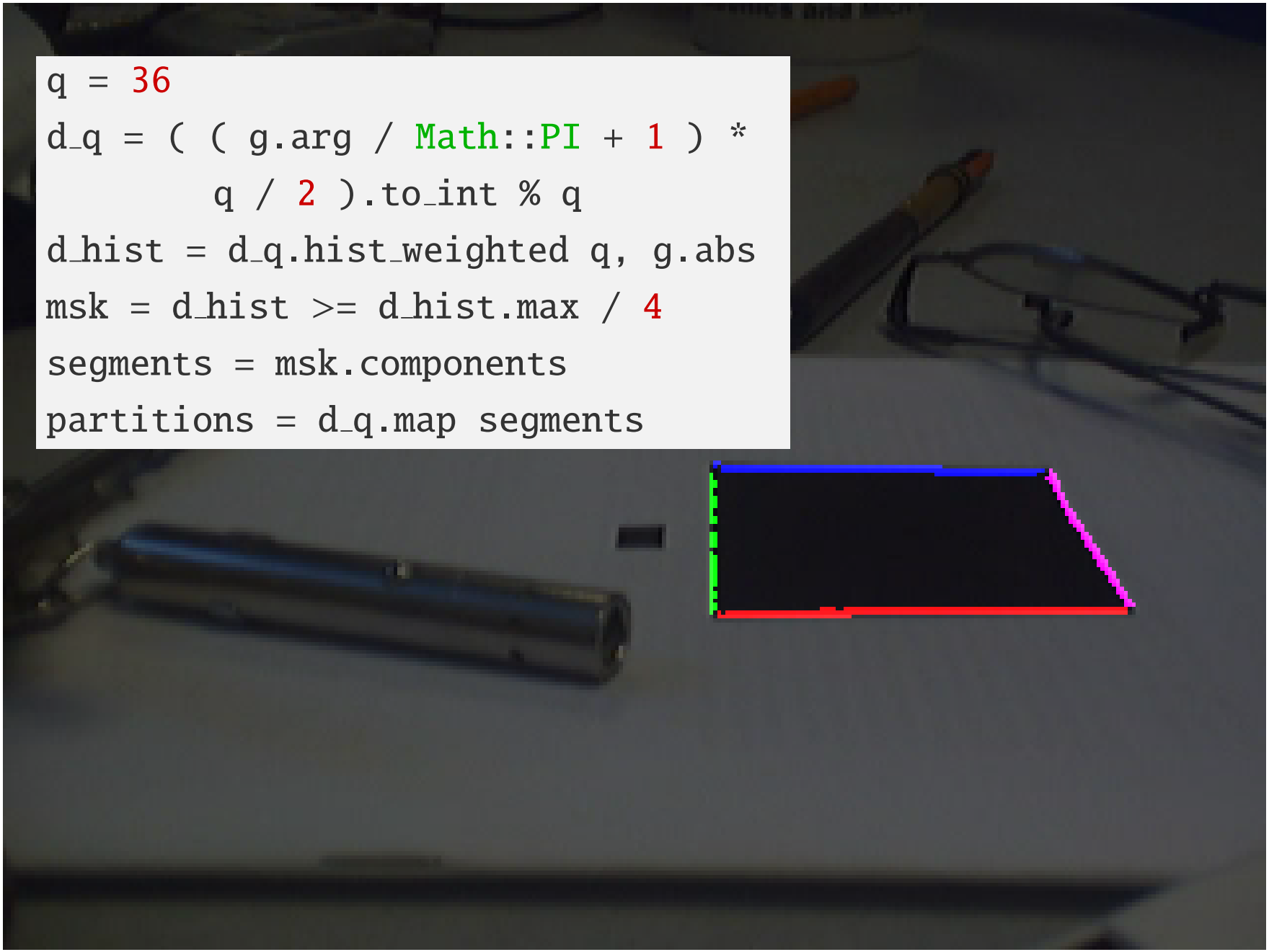
# Augmented Reality Example

## Compute Gradients



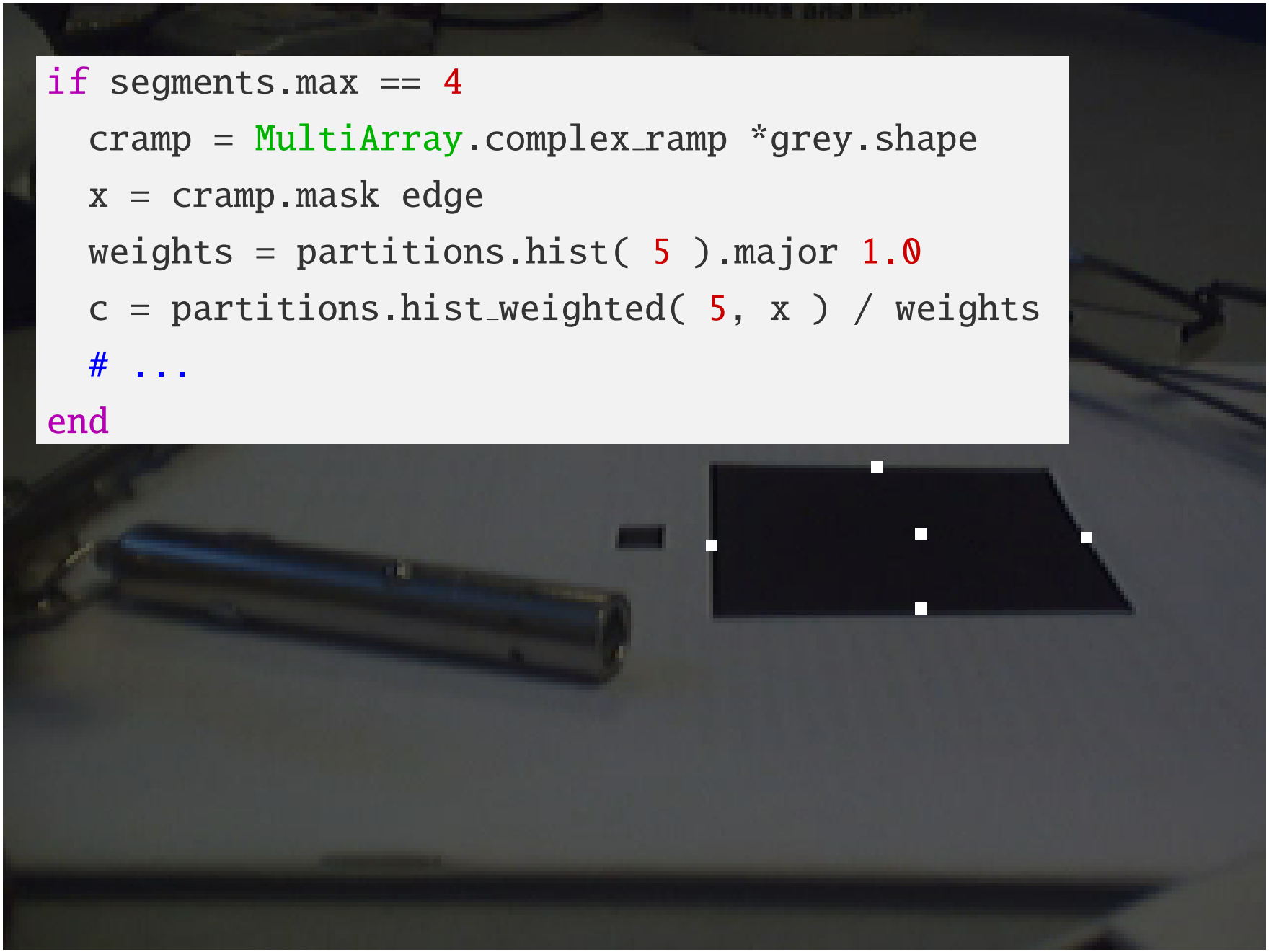
# Augmented Reality Example

## Group Dominant Orientations



# Augmented Reality Example

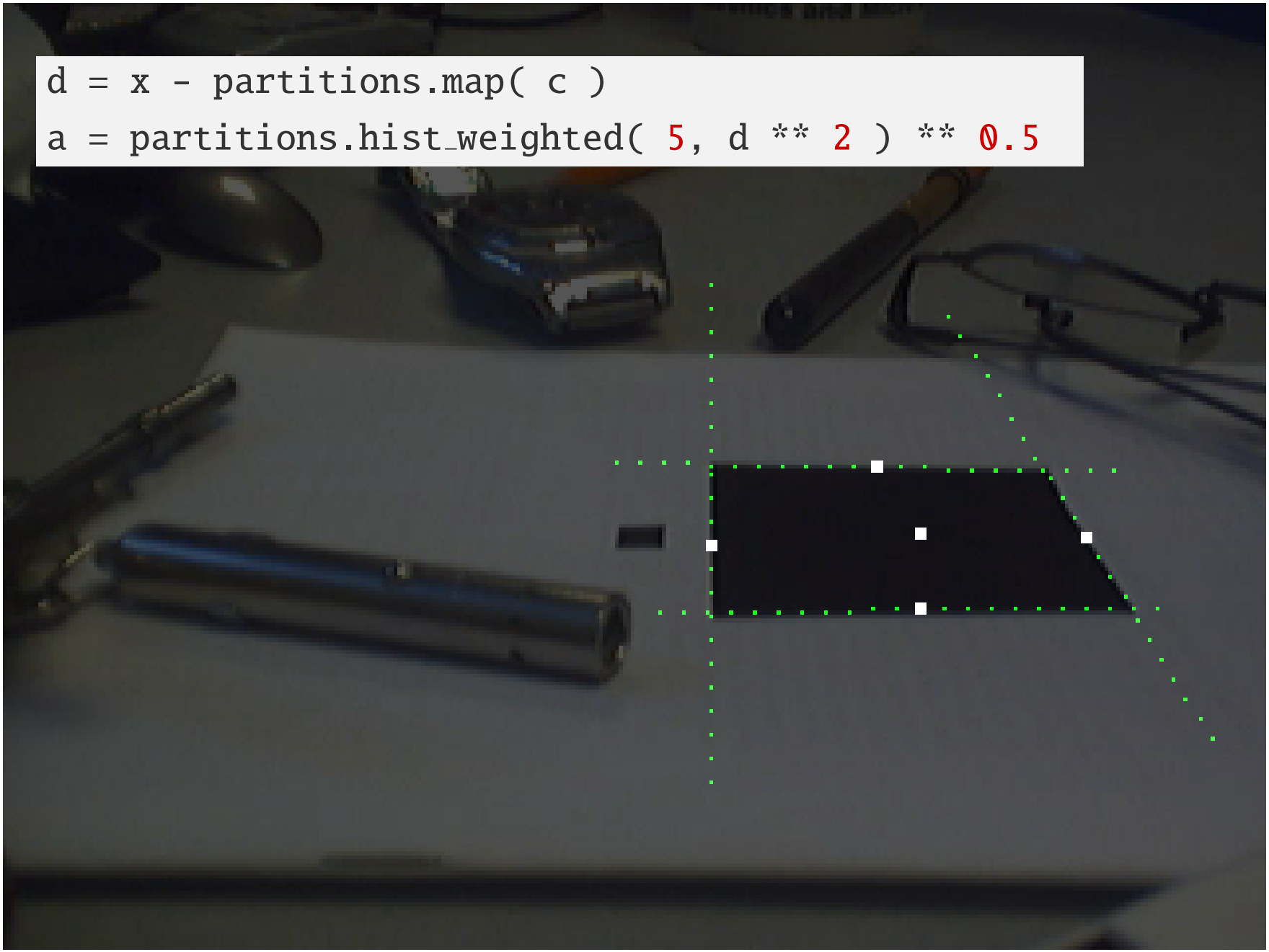
## Centre of each Line



```
if segments.max == 4
  cramp = MultiArray.complex_ramp *grey.shape
  x = cramp.mask edge
  weights = partitions.hist( 5 ).major 1.0
  c = partitions.hist_weighted( 5, x ) / weights
  # ...
end
```

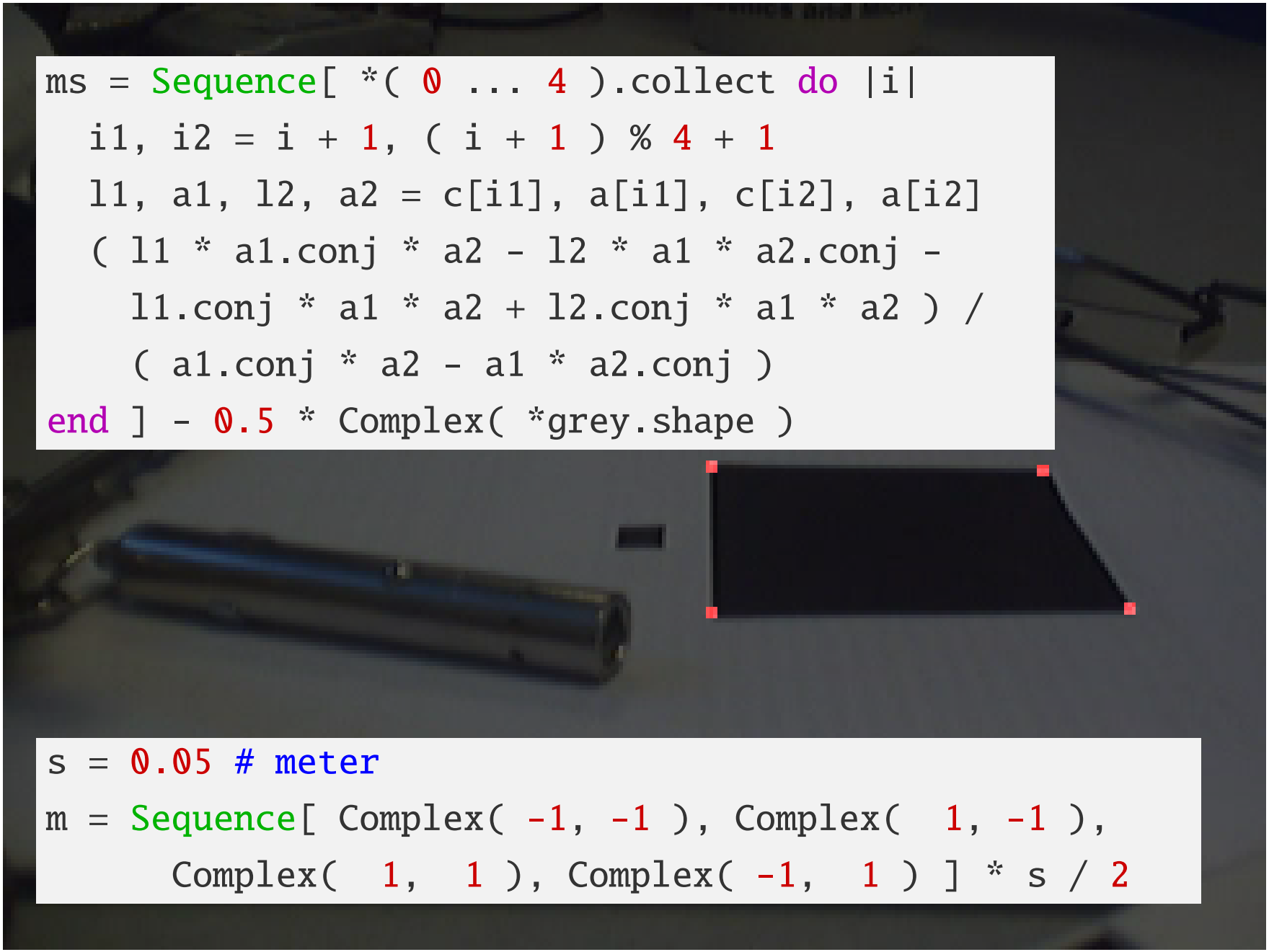
# Augmented Reality Example

## Angle of each Line



# Augmented Reality Example

## Intersections



Hornets Eye

# Augmented Reality Example

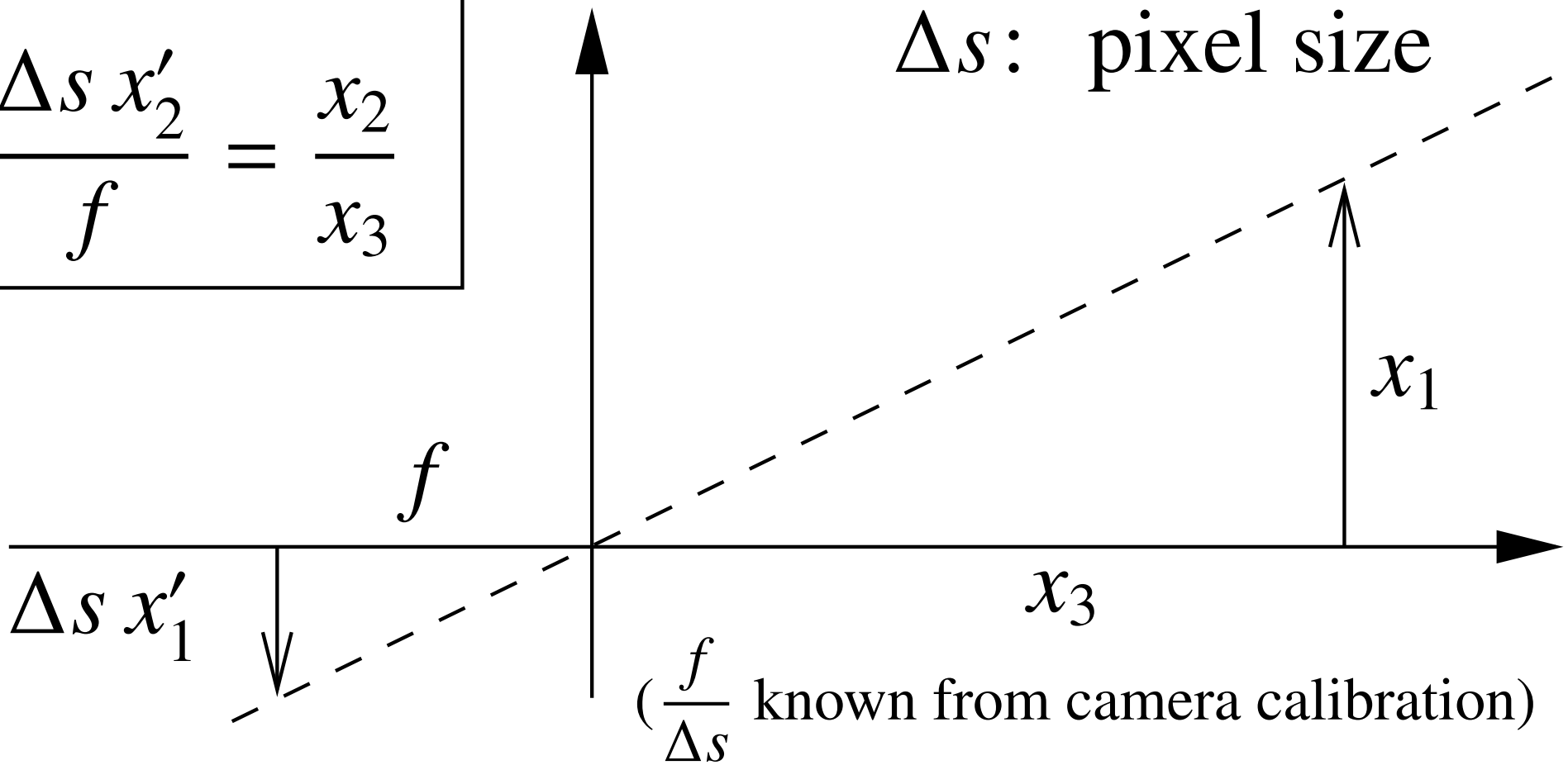
## 3D Pose: Pinhole Camera Model

$$\frac{\Delta s\, x'_1}{f} = \frac{x_1}{x_3}$$

$$\frac{\Delta s\, x'_2}{f} = \frac{x_2}{x_3}$$

$f$ : focal length

$\Delta s$: pixel size



Hornets Eye

# Augmented Reality Example

## 3D Pose: Homogeneous Coordinates

$$x_3\, x'_1 = \frac{f}{\Delta s}\, x_1$$

$$x_3\, x'_2 = \frac{f}{\Delta s}\, x_2$$

$$\lambda\, x'_1 = \frac{f}{\Delta s}\, x_1$$

$$\Leftrightarrow \exists \lambda \in \mathbb{R}/\{0\} : \quad \lambda\, x'_2 = \frac{f}{\Delta s}\, x_2$$

$$\lambda = x_3$$

$$\Leftrightarrow \exists \lambda \in \mathbb{R}/\{0\} : \quad \lambda \begin{pmatrix} x'_1 \\ x'_2 \\ 1 \end{pmatrix} = \underbrace{\begin{pmatrix} f/\Delta s & 0 & 0 \\ 0 & f/\Delta s & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{intrinsic camera parameters}} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$$

Hornets Eye

# Augmented Reality Example

## 3D Pose: (Additional) Affine Transform

$$\exists \lambda \in \mathbb{R}/\{0\} : \lambda \begin{pmatrix} x'_1 \\ x'_2 \\ 1 \end{pmatrix} = \begin{pmatrix} f/\Delta s & 0 & 0 \\ 0 & f/\Delta s & 0 \\ 0 & 0 & 1 \end{pmatrix} \left( \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} t_1 \\ t_2 \\ t_3 \end{pmatrix} \right)$$

$$\Leftrightarrow \exists \lambda \in \mathbb{R}/\{0\} : \lambda \begin{pmatrix} x'_1 \\ x'_2 \\ 1 \end{pmatrix} = \begin{pmatrix} f/\Delta s & 0 & 0 \\ 0 & f/\Delta s & 0 \\ 0 & 0 & 1 \end{pmatrix} \underbrace{\begin{pmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{pmatrix}}_{\text{extrinsic camera parameters}} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} x'_1 \\ x'_2 \end{pmatrix} \text{ is } \begin{pmatrix} m'_{11} \\ m'_{12} \end{pmatrix}, \begin{pmatrix} m'_{21} \\ m'_{22} \end{pmatrix}, \ldots, \begin{pmatrix} m'_{41} \\ m'_{42} \end{pmatrix} \text{ and } \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \text{ is } \begin{pmatrix} m_{11} \\ m_{12} \\ 0 \end{pmatrix}, \begin{pmatrix} m_{21} \\ m_{22} \\ 0 \end{pmatrix}, \ldots, \begin{pmatrix} m_{41} \\ m_{42} \\ 0 \end{pmatrix}$$

Hornets Eye

# Augmented Reality Example

## 3D Pose: Planar Homography I/II

### Problem: Minimize $\epsilon_{ij}$

$$\exists \lambda_i \in \mathbb{R}/\{0\} : \lambda_i \left( \begin{pmatrix} m'_{i1} \\ m'_{i2} \\ 1 \end{pmatrix} + \begin{pmatrix} \epsilon_{i1} \\ \epsilon_{i2} \\ 0 \end{pmatrix} \right) = \begin{pmatrix} f/\Delta s & 0 & 0 \\ 0 & f/\Delta s & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{pmatrix} \begin{pmatrix} m_{i1} \\ m_{i2} \\ 0 \\ 1 \end{pmatrix}$$

$$\Leftrightarrow \exists \lambda_i \in \mathbb{R}/\{0\} : \lambda_i \left( \begin{pmatrix} m'_{i1} \\ m'_{i2} \\ 1 \end{pmatrix} + \begin{pmatrix} \epsilon_{i1} \\ \epsilon_{i2} \\ 0 \end{pmatrix} \right) = \underbrace{\begin{pmatrix} f/\Delta s & 0 & 0 \\ 0 & f/\Delta s & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ r_{31} & r_{32} & t_3 \end{pmatrix}}_{=:\mathcal{H}} \begin{pmatrix} m_{i1} \\ m_{i2} \\ 1 \end{pmatrix}$$

$$\Leftrightarrow \exists \lambda_i \in \mathbb{R}/\{0\} : \lambda_i \left( \begin{pmatrix} m'_{i1} \\ m'_{i2} \\ 1 \end{pmatrix} + \begin{pmatrix} \epsilon_{i1} \\ \epsilon_{i2} \\ 0 \end{pmatrix} \right) = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{33} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} \begin{pmatrix} m_{i1} \\ m_{i2} \\ 1 \end{pmatrix}, i \in \{1, 2, \ldots, 4\}$$

Hornets Eye

# Augmented Reality Example

## 3D Pose: Planar Homography II/II

$$\Leftrightarrow \underbrace{(h_{31}\, m_{i1} + h_{32}\, m_{i2} + h_{33})}_{\lambda_i} \left( \begin{pmatrix} m'_{i1} \\ m'_{i2} \end{pmatrix} + \begin{pmatrix} \epsilon_{i1} \\ \epsilon_{i2} \end{pmatrix} \right) = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{33} \end{pmatrix} \begin{pmatrix} m_{i1} \\ m_{i2} \\ 1 \end{pmatrix}$$

assuming $\lambda_1 \approx \lambda_2 \approx \ldots \approx \lambda_4$

this is approximately the same as

**Problem: Minimize $\widetilde{\epsilon}_{ij}$**

$$(h_{31}\, m_{i1} + h_{32}\, m_{i2} + h_{33}) \begin{pmatrix} m'_{i1} \\ m'_{i2} \end{pmatrix} + \begin{pmatrix} \widetilde{\epsilon}_{i1} \\ \widetilde{\epsilon}_{i2} \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{33} \end{pmatrix} \begin{pmatrix} m_{i1} \\ m_{i2} \\ 1 \end{pmatrix}$$

$$\Leftrightarrow \begin{pmatrix} \widetilde{\epsilon}_{i1} \\ \widetilde{\epsilon}_{i2} \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{33} \end{pmatrix} \begin{pmatrix} m_{i1} \\ m_{i2} \\ 1 \end{pmatrix} - (h_{31}\, m_{i1} + h_{32}\, m_{i2} + h_{33}) \begin{pmatrix} m'_{i1} \\ m'_{i2} \end{pmatrix}$$

# Augmented Reality Example

## 3D Pose: Singular Value Decomposition

$$\underbrace{\begin{pmatrix} m_{11} & m_{12} & 1 & 0 & 0 & 0 & -m'_{11}m_{11} & -m'_{11}m_{12} & -m'_{11} \\ 0 & 0 & 0 & m_{11} & m_{12} & 1 & -m'_{12}m_{11} & -m'_{12}m_{12} & -m'_{12} \\ m_{21} & m_{22} & 1 & 0 & 0 & 0 & -m'_{21}m_{21} & -m'_{21}m_{22} & -m'_{21} \\ 0 & 0 & 0 & m_{21} & m_{22} & 1 & -m'_{22}m_{21} & -m'_{22}m_{22} & -m'_{22} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ m_{41} & m_{42} & 1 & 0 & 0 & 0 & -m'_{41}m_{41} & -m'_{41}m_{42} & -m'_{41} \\ 0 & 0 & 0 & m_{41} & m_{42} & 1 & -m'_{42}m_{41} & -m'_{42}m_{42} & -m'_{42} \end{pmatrix}}_{=:\mathcal{M}} \underbrace{\begin{pmatrix} h_{11} \\ h_{12} \\ \vdots \\ h_{33} \end{pmatrix}}_{=:\vec{h}} = \begin{pmatrix} \widetilde{\epsilon}_{11} \\ \widetilde{\epsilon}_{12} \\ \widetilde{\epsilon}_{21} \\ \widetilde{\epsilon}_{22} \\ \vdots \\ \widetilde{\epsilon}_{41} \\ \widetilde{\epsilon}_{42} \end{pmatrix}$$

$\|\vec{h}\| = \mu \neq 0$ to avoid trivial solution

I.e. find $\vec{h} \in \mathbb{R}^9 : \|\mathcal{M}\vec{h}\|$ minimal and $\|\vec{h}\| = \mu$

**Solution:** Perform SVD $\mathcal{M} = \mathcal{U}\Sigma\mathcal{V}^*$ and choose $\vec{h} = \mu\,\vec{v}_9$ where $\vec{v}_9$ is right-handed singular vector with the smallest singular value $\sigma_9$

# Augmented Reality Example

## 3D Pose: 3D Homography

$$\mathcal{H} = \mu \begin{pmatrix} v_{91} & v_{92} & v_{93} \\ v_{94} & v_{95} & v_{96} \\ v_{97} & v_{98} & v_{99} \end{pmatrix} = \begin{pmatrix} f/\Delta s & 0 & 0 \\ 0 & f/\Delta s & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ r_{31} & r_{32} & t_3 \end{pmatrix}$$

$$\|\vec{r}_1\| = \|\vec{r}_2\| = 1$$

$$\vec{r}_3 = \vec{r}_1 \times \vec{r}_2$$

$$t_3 > 0$$

$$\vec{r}_3^{\top} \vec{t} \leq 0$$

$\Rightarrow$ Enough information to estimate 3D homography!

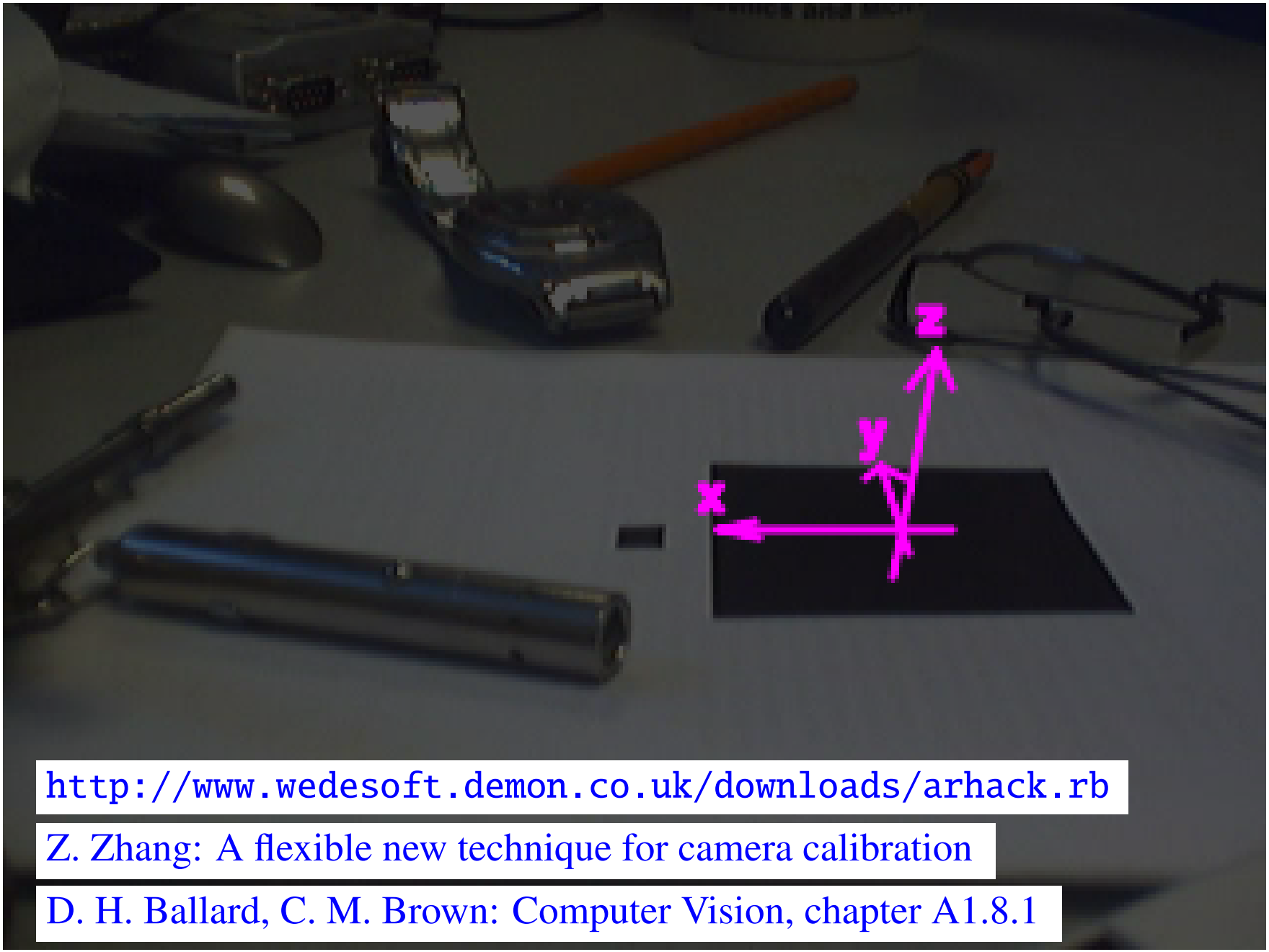

# Augmented Reality Example

## Source Code

```
constraints = []
for i in 0 ... 4 do
  constraints.push [ m[i].real, m[i].imag, 1.0, 0.0, 0.0, 0.0,
    -ms[i].real * m[i].real, -ms[i].real * m[i].imag, -ms[i].real ]
  constraints.push [ 0.0, 0.0, 0.0, m[i].real, m[i].imag, 1.0,
    -ms[i].imag * m[i].real, -ms[i].imag * m[i].imag, -ms[i].imag ]
end
h = Matrix[ *constraints ].svd[ 2 ].row( 8 ).reshape 3, 3
fs = 1.2 * 320 # focal length divided by pixel size
intr = Matrix[ [ fs, 0.0, 0.0 ], [ 0.0, fs, 0.0 ], [ 0.0, 0.0, 1.0 ] ]
rt = intr.inv * h
scale = 0.5 * ( rt.column( 0 ).norm + rt.column( 1 ).norm )
t = rt.column( 2 ) / scale
e1, e2 = rt.column( 0 ).normalise, e2 = rt.column( 1 ).normalise
e3 = e1.x e2
e1, e2, e3 = -e2, e1, -e3 if e3.inner_product( t ) > 0
extr = Matrix[ [ e1[0], e2[0], e3[0], t[0] ], [ e1[1], e2[1], e3[1], t[1] ],
               [ e1[2], e2[2], e3[2], t[2] ], [   0.0,   0.0,   0.0,  1.0 ] ]
```

# Augmented Reality Example

## Result



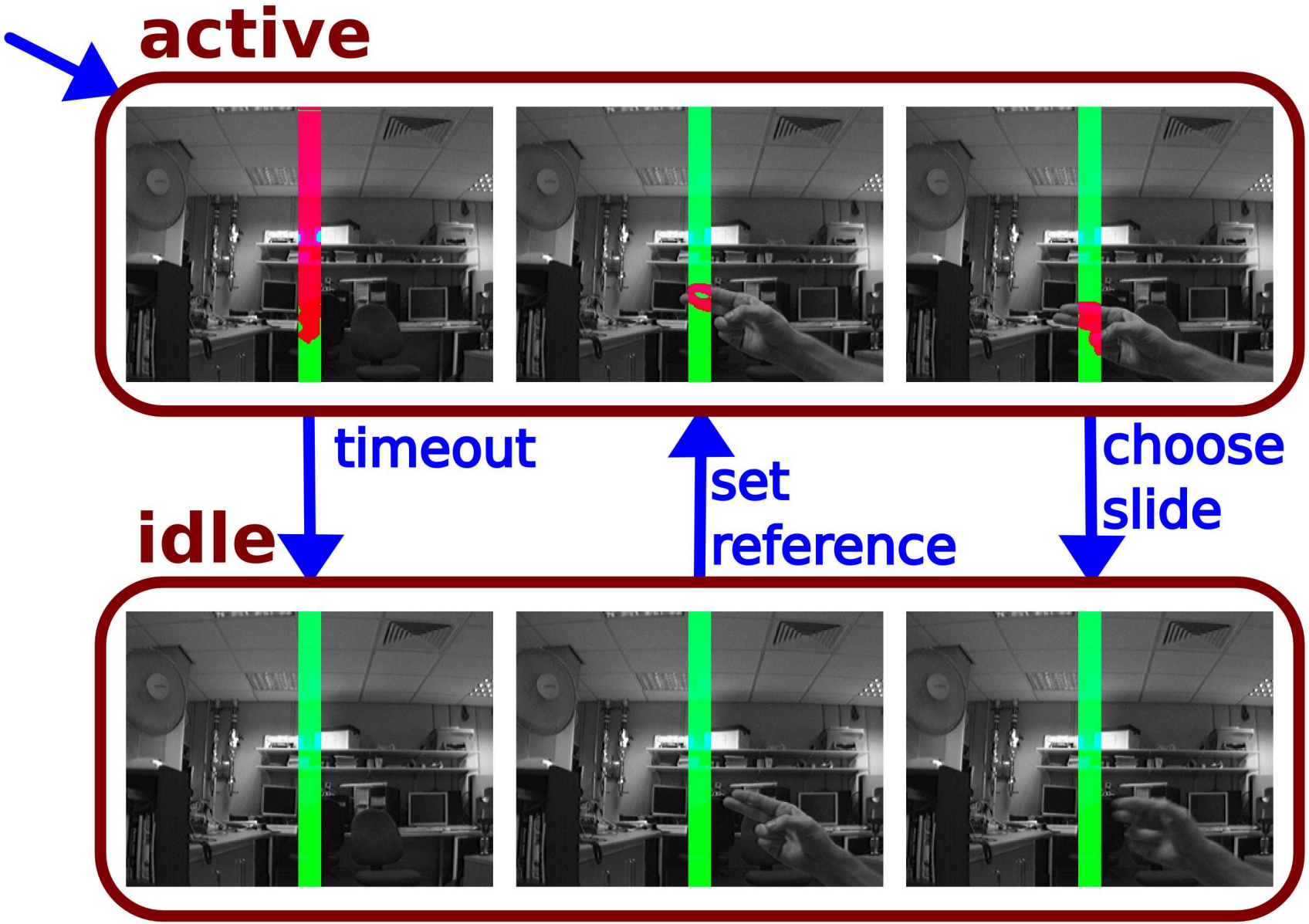

http://www.wedesoft.demon.co.uk/downloads/arhack.rb

Z. Zhang: A flexible new technique for camera calibration

D. H. Ballard, C. M. Brown: Computer Vision, chapter A1.8.1

# Presenter

## States




http://www.wedesoft.demon.co.uk/downloads/sensor.rb

Hornets Eye

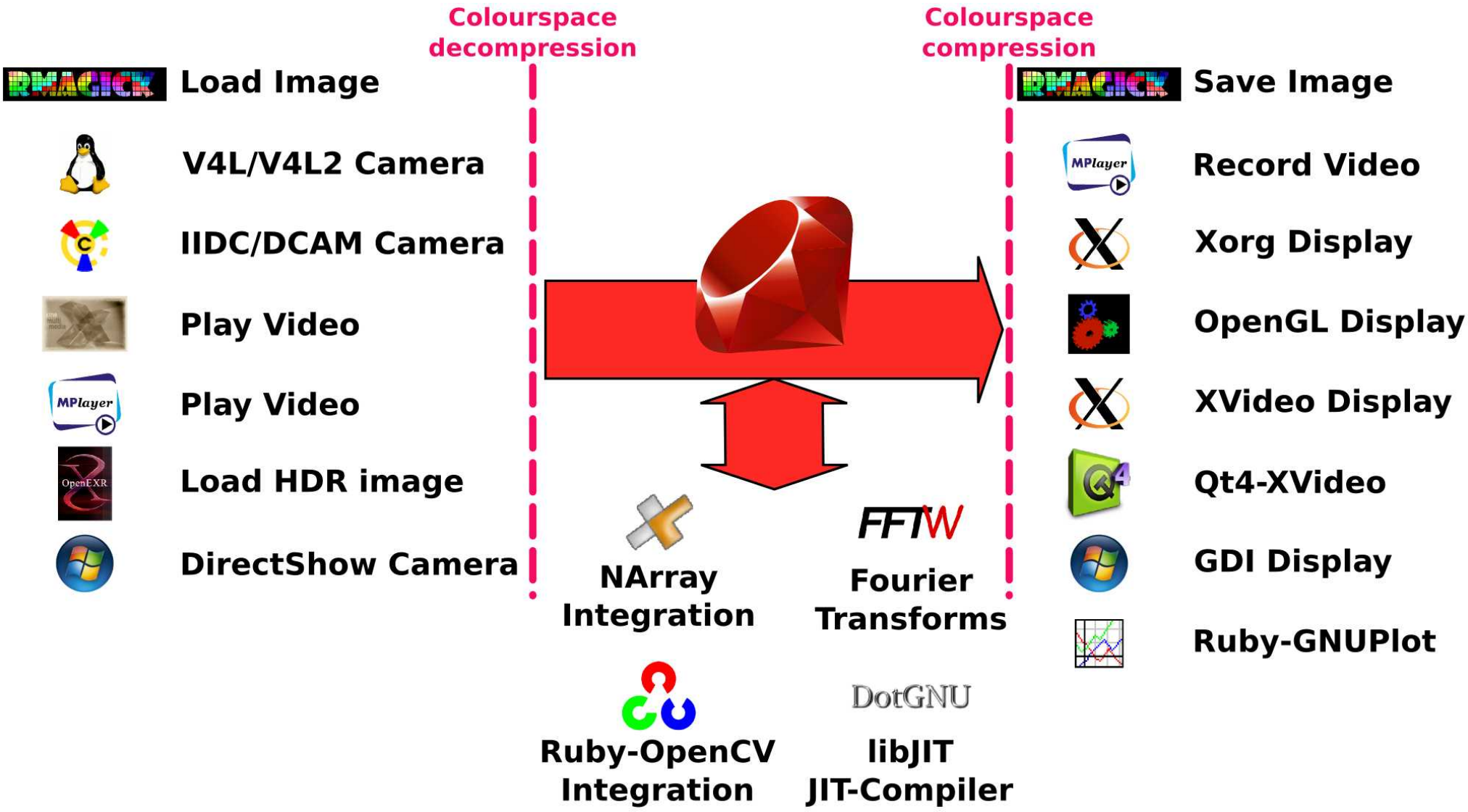
# Presenter

## Source Code (simplified)

```
input = DC1394Input.new
w, h, o = 20, input.height, input.width / 2 - 10
box = [ o ... o + w, 0 ... h ]
15.times { input.read }; bg = input.read_ubyte[ *box ]
ramp = Sequence.int( h ).indgen!.repmat( w ).roll
X11Display.show do
  img = input.read_ubytergb
  slice = ( img[ *box ].to_sint - bg ).gauss_blur( 2 ).abs >= 12
  n = slice.to_ubyte.sum
  if n > 20
    y = ramp.mask( slice ).sum / n
    print "#{ "%4d" % y }\r"; STDOUT.flush
  end
  img[ *box ].r = slice.to_ubyte * 255
  img[ *box ].g = slice.not.to_ubyte * 255
  img
end
```

Hornets Eye

# Input/Output



# Closures

**Python + OpenCV**

```
import sys
from opencv import cv
from opencv import highgui
highgui.cvNamedWindow( 'Camera' )
capture = highgui.cvCreateCameraCapture( -1 )
while 1:
    frame = highgui.cvQueryFrame( capture )
    gray = cv.cvCreateImage( cv.cvSize( frame.width, frame.height), 8, 1 )
    cv.cvCvtColor( frame, gray, cv.CV_BGR2GRAY )
    highgui.cvShowImage( 'Camera', gray )
    if highgui.cvWaitKey( 5 ) > 0:
        break
```

---

**Ruby + HornetsEye**

```
require 'hornetseye'
include Hornetseye
capture = V4L2Input.new
X11Display.show( :title => 'Camera' ) { capture.read.to_ubyte }
```

# Colourspace Conversions

$Y$

$Y + C_r$

$Y + C_b$

$Y + C_r + C_b$

| | Channel | Resolution |
|---|---|---|
| $Y$ | Luminance | high |
| $C_r$ | Chroma red | low |
| $C_b$ | Chroma blue | low |

See also: http://fourcc.org/

$$\begin{pmatrix} Y \\ C_b \\ C_r \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ -0.168736 & -0.331264 & 0.500 \\ 0.500 & -0.418688 & -0.081312 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} + \begin{pmatrix} 0 \\ 128 \\ 128 \end{pmatrix}$$


# Lazy Computation

```ruby
class Seq
  def Seq.new( *arr )
    unless Thread.current[ :lazy ]
      super *arr
    else
      Lazy.new( *arr ) { |x| x }
    end
  end
  def initialize( *arr )
    @arr = arr
  end
  def -@
    Seq.new *@arr.collect { |x| -x }
  end
end
```

```ruby
class Lazy
  def initialize( *arr, &p )
    @arr, @p = arr, p
  end
  def demand
    Seq.new *@arr.collect { |i| @p.call i }
  end
  def -@
    Lazy.new( *@arr ) { |i| -@p.call( i ) }
  end
end
def lazy
  previous = Thread.current[ :lazy ]
  Thread.current[ :lazy ] = true
  retval = yield
  Thread.current[ :lazy ] = previous
  retval.demand
end
```




# Credits

## Credits

Aiden Lockwood, Aleksey Demakov, Annemie Wedekind, Balasundram Amavasai, Beverly Inkson, Chinwe Lucy Ozoegwu, Damien Douxchamps, Daniel Martín Marín, Géraud De La Mensbruge, Gerhard Wedekind, Hussein Abdul-Rahman, Jing Jing Wang, Jon Travis, Jong Peng, Juan Roldan, Julien Demarest, Julien Faucher, Julien Lacheray, Ken Dutton, Kim Chuan Lim, Kirill Kononenko, Klaus Treichel, Manuel Boissenin, Martin Howarth, Matthias Stumpf, Michael Doronin, Ralph Gay, Richard Dale, Sonia Fernández Rodríguez, Tan Kang Song, Ushakiran Soutapalli, Volkan Karaca, Warren Jasper, Zineb Saghi, ...

http://www.wedesoft.demon.co.uk/hornetseye-api/

http://rubyforge.org/projects/hornetseye/

http://sourceforge.net/projects/hornetseye/

http://launchpad.net/hornetseye/

http://raa.ruby-lang.org/project/hornetseye/

http://www.ohloh.net/p/hornetseye/