Welcome back! Link to Attendance Form ↓

Low Battery

10% battery remaining.

Things that drain battery life

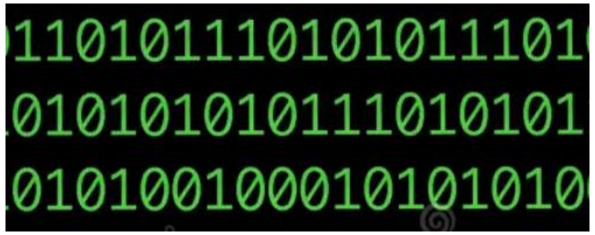
Connecting to WiFi

Performing computations

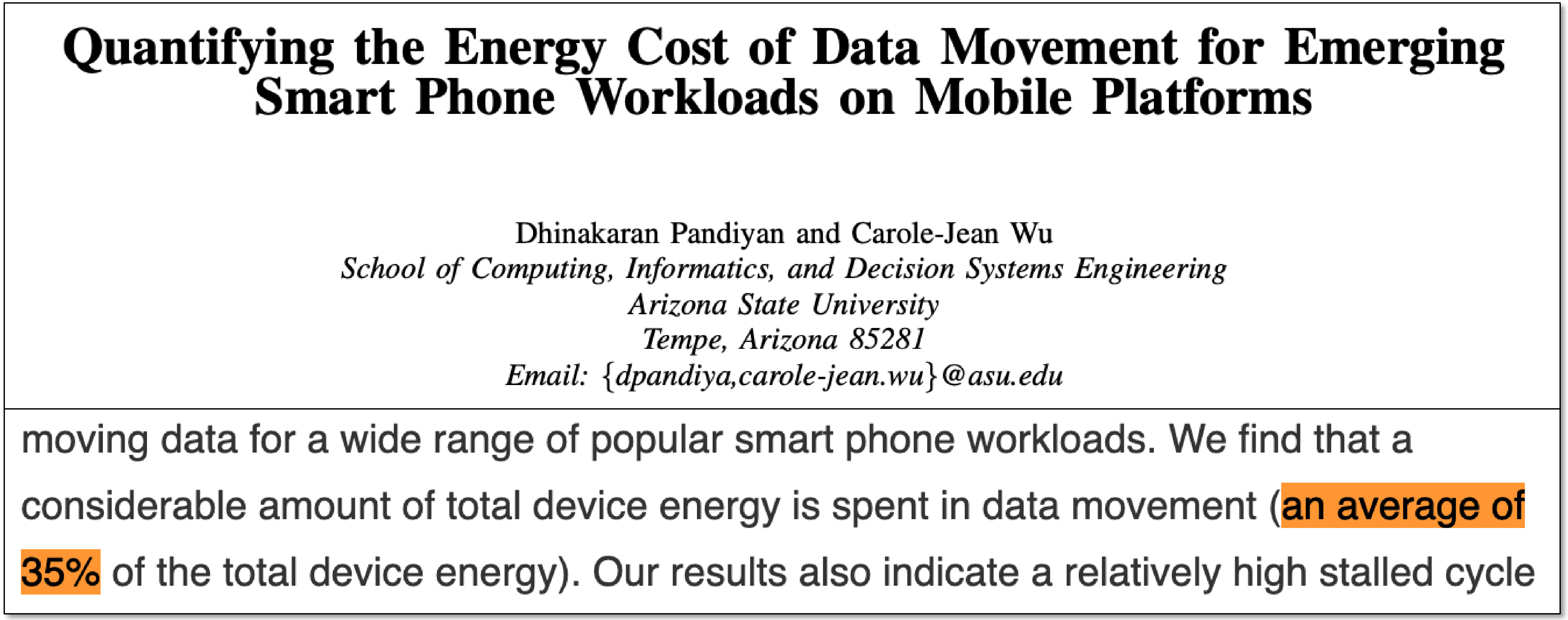
$$f(x) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\frac{n\pi x}{L} + b_n \sin\frac{n\pi x}{L}\right)$$

Powering the display

Copying data?? 🤔



Copying data is expensive

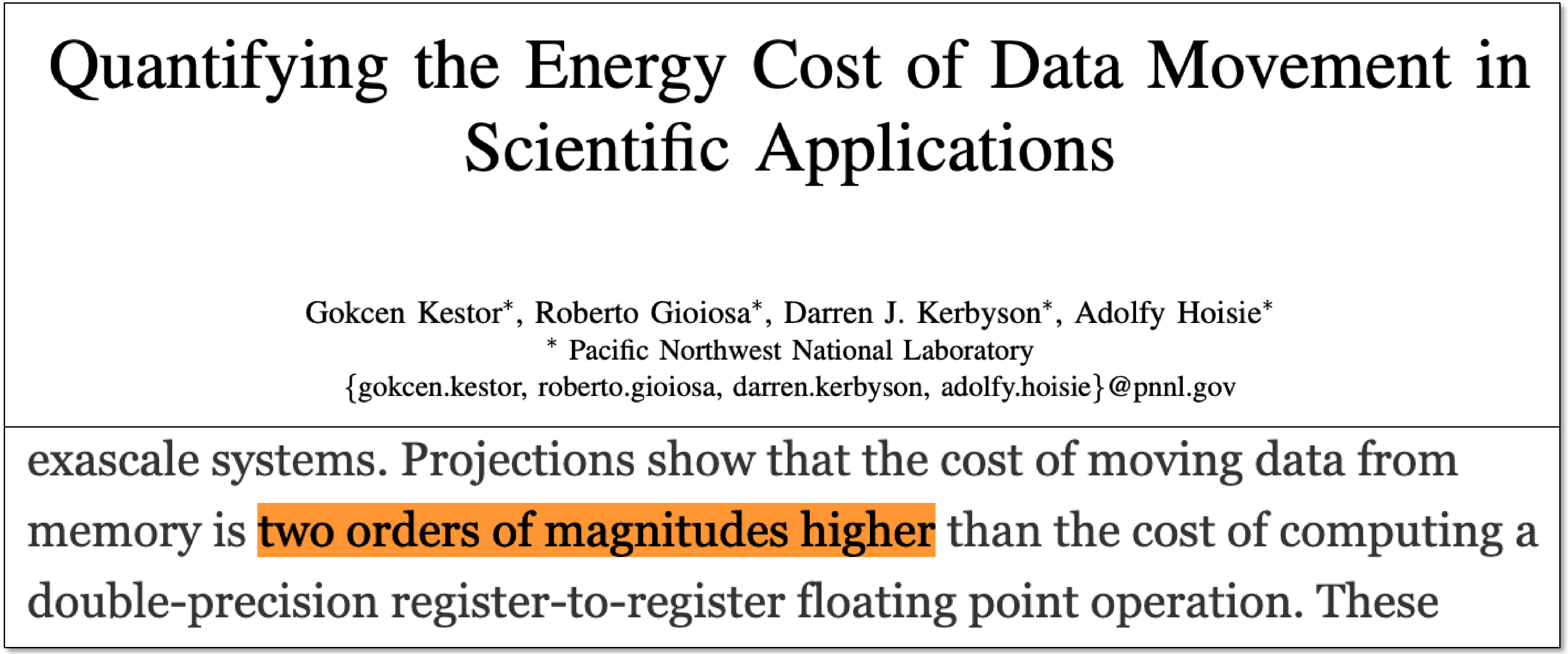

Quantifying the Energy Cost of Data Movement for Emerging Smart Phone Workloads on Mobile Platforms

Dhinakaran Pandiyan and Carole-Jean Wu
School of Computing, Informatics, and Decision Systems Engineering
Arizona State University
Tempe, Arizona 85281
Email: {dpandiya,carole-jean.wu}@asu.edu

moving data for a wide range of popular smart phone workloads. We find that a considerable amount of total device energy is spent in data movement (an average of 35% of the total device energy). Our results also indicate a relatively high stalled cycle

[source]

Copying data is expensive


Quantifying the Energy Cost of Data Movement in Scientific Applications

Gokcen Kestor*, Roberto Gioiosa*, Darren J. Kerbyson*, Adolfy Hoisie*
* Pacific Northwest National Laboratory
{gokcen.kestor, roberto.gioiosa, darren.kerbyson, adolfy.hoisie}@pnnl.gov

exascale systems. Projections show that the cost of moving data from memory is two orders of magnitudes higher than the cost of computing a double-precision register-to-register floating point operation. These

[source]

Why does it matter?

How can we avoid needlessly copying data?

Lecture 13: Move Semantics

CS106L, Winter 2025

Today’s Agenda

- SMFs Recap
  - What is a special member function?
- The Problem
  - How do our SMFs cause unnecessary copies?
- `lvalues` and `rvalues`
  - How does C++ distinguish between persistent and temporary objects?
- Move Semantics
  - How can we avoid making unnecessary copies? And a code demo!
- `std::move` and SMFs
  - How can we ”opt-in” to move semantics? Which SMFs should I define?

What questions do you have?

`bjarne_about_to_raise_hand`

SMFs Recap

Last Time

- Special member functions handle the class lifecycle
  - Copy constructor
    ```
    Type::Type(const Type& other);
    Type a = b;
    ```
  - Copy assignment operator
    ```
    Type& Type::operator=(const Type& other);
    a = b;
    ```
  - Destructor
    ```
    Type::~Type();
    ```
- Compiler creates these for us
  - But… if we’re managing memory, we need to override

Introducing... the Photo class

```
class Photo {
public:
   Photo(int width, int height);
   Photo(const Photo& other);
   Photo& operator=(const Photo& other);
   ~Photo();
private:
   int width;
   int height;
   int* data;
};
```

Photo Constructor

```
Photo::Photo(int width, int height)
   : width(width)
   , height(height)
   , data(new int[width * height])
{}
```

Creates a **brand new photo** and allocates memory for its pixels!

Photo SMF: Copy Constructor

```
Photo::Photo(const Photo& other)
  : width(other.width)
  , height(other.height)
  , data(new int[width * height])
{
  std::copy(other.data, other.data + width * height, data);
}
```

Creates a **new photo from an existing one,** creating a copy of its data!

Photo SMF: Copy Assignment

```cpp
Photo &Photo::operator=(const Photo& other) {
   // Check for self assignment
   if (this == &other) return *this;

   delete[] data; // Clean up old pixels!

   // Copy over new pixels!
   width = other.width;
   height = other.height;
   data = new int[width * height];
   std::copy(other.data, other.data + width * height, data);
   return *this;
}
```

Replaces a photo's contents with the contents of another, cleaning up its own data before copying the new one!

Photo SMF: Destructor

```
Photo::~Photo()
{
  delete[] data;
}
```

Cleans up this photo’s data so we don’t leak memory!

What questions do you have?

`bjarne_about_to_raise_hand`

Your Turn

What special member functions get called at **(A)** and **(B)** below?

```
Photo takePhoto();

int main() {
   Photo selfie = takePhoto();   // (A)      Copy Destruct
   Photo retake(0, 0);
   retake = takePhoto();         // (B)      Assign Destruct
}
```

A Small Aside: Return Value Optimization

- This line

```
Photo selfie = takePhoto();
```

  might not actually call **copy-constructor** + **destructor**
- This is due to a compiler optimization called return-value optimization (RVO)
- For the purposes of this lecture, we will pretend that it does!

Key Idea: The return value of a function is temporary (it's destroyed before the next line)

```
Photo selfie = takePhoto();
```

The compiler is going to clean this object up before moving onto the next line!

What questions do you have?

`bjarne_about_to_raise_hand`

The Problem

The Problem

```
Photo selfie = takePhoto();
```

The Problem

Photo
- width = 3840
- height = 2160
- data = 0x1024c3bd

```
Photo selfie = takePhoto();
```

The Problem

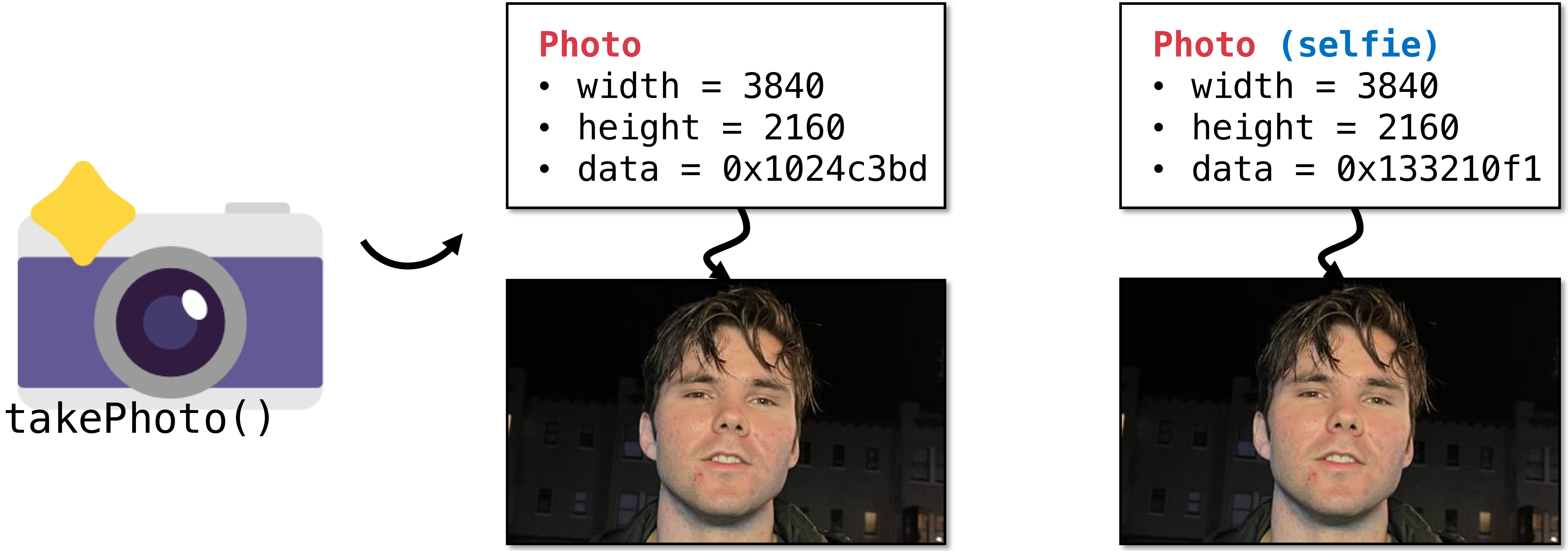

takePhoto()

Photo
- width = 3840
- height = 2160
- data = 0x1024c3bd

Photo (selfie)
- width = 3840
- height = 2160
- data = 0x133210f1

```
Photo selfie = takePhoto(); // Copy constructor
```

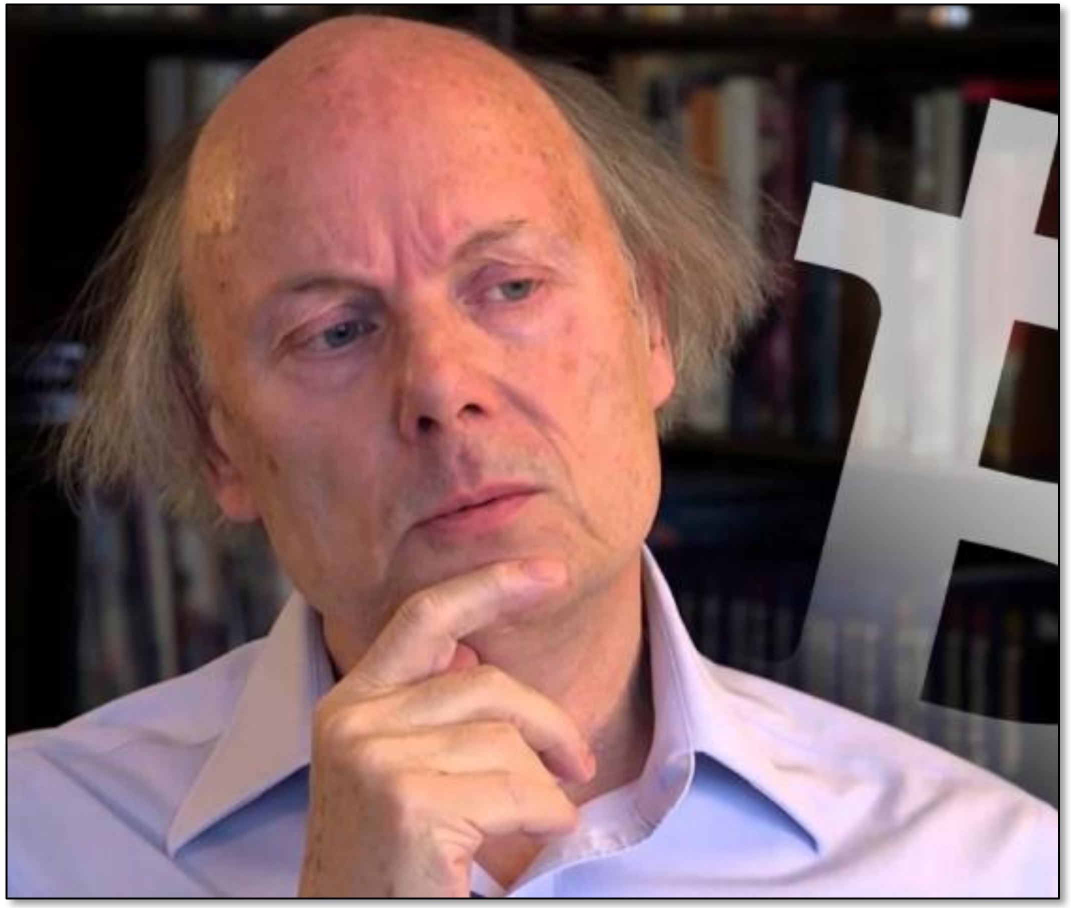
The Problem

☠ Photo
- width = 3840
- height = 2160
- data = 0x1024c3bd

Photo (selfie)
- width = 3840
- height = 2160
- data = 0x133210f1

```
Photo selfie = takePhoto(); // Destructor
```

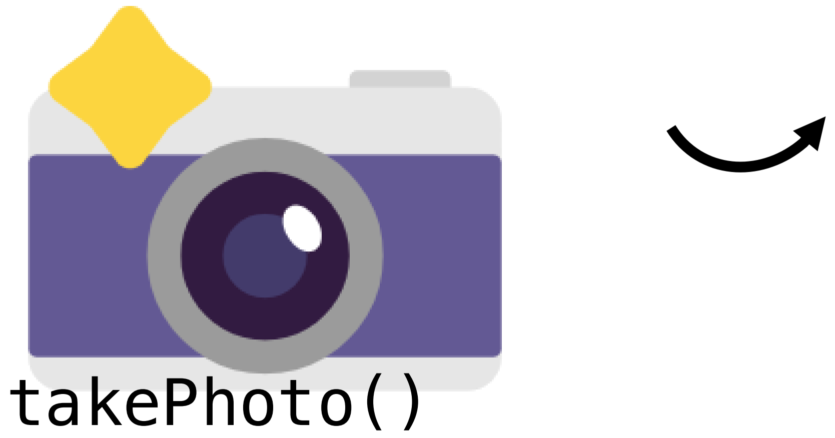
The Problem



`concerned_bjarne`

What if we could reuse the memory instead?

The Solution: Move Semantics



```
Photo
• width = 3840
• height = 2160
• data = 0x1024c3bd
```

```
Photo selfie = takePhoto();
```

The Problem

takePhoto()

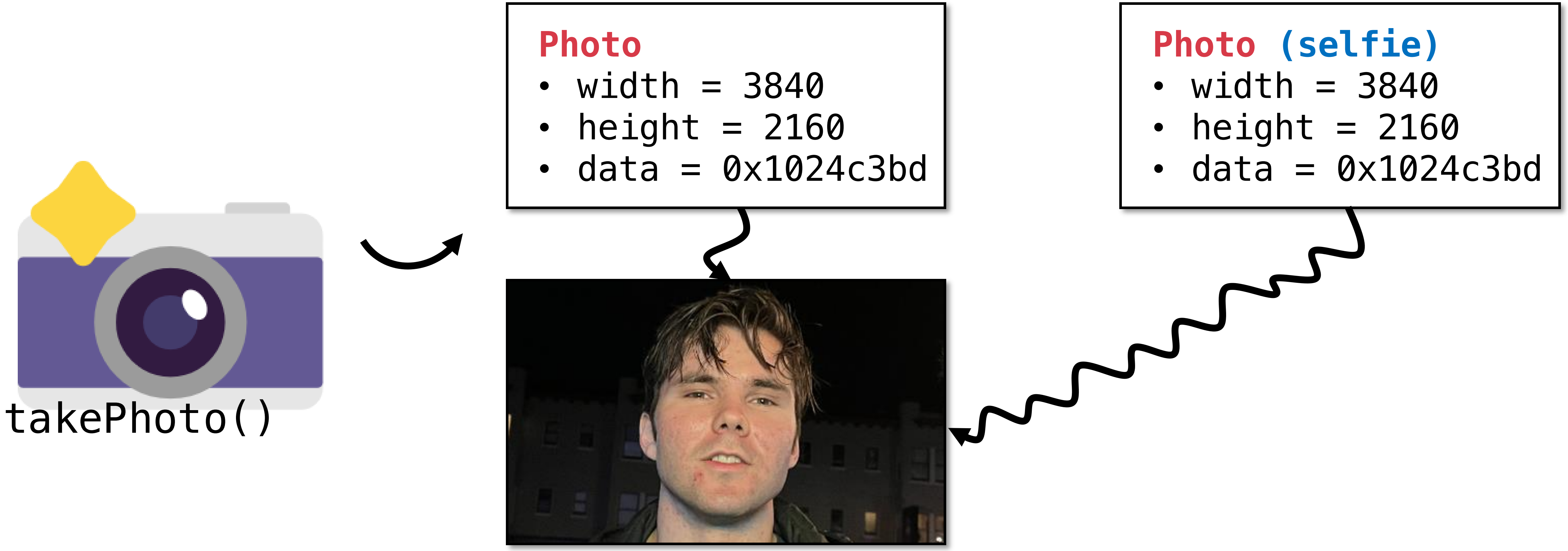
```
Photo
• width = 3840
• height = 2160
• data = 0x1024c3bd
```

```
Photo (selfie)
• width = 3840
• height = 2160
• data = 0x1024c3bd
```

Instead of **copying data**, let’s **steal it!**

`Photo selfie = takePhoto(); //` ~~`Copy`~~ **`Move`** `constructor`

The Problem



```
Photo
• width = 3840
• height = 2160
• data = 0x1024c3bd
```

```
Photo (selfie)
• width = 3840
• height = 2160
• data = 0x1024c3bd
```

```
Photo selfie = takePhoto(); // Destructor
```

The Problem

takePhoto()

☠ Photo
- width = 3840
- height = 2160
- data = 0x1024c3bd

Photo (selfie)
- width = 3840
- height = 2160
- data = 0x1024c3bd

Oh no… the destructor of takePhoto() **deletes** our stolen data

```
Photo selfie = takePhoto(); // Destructor
```

The Problem

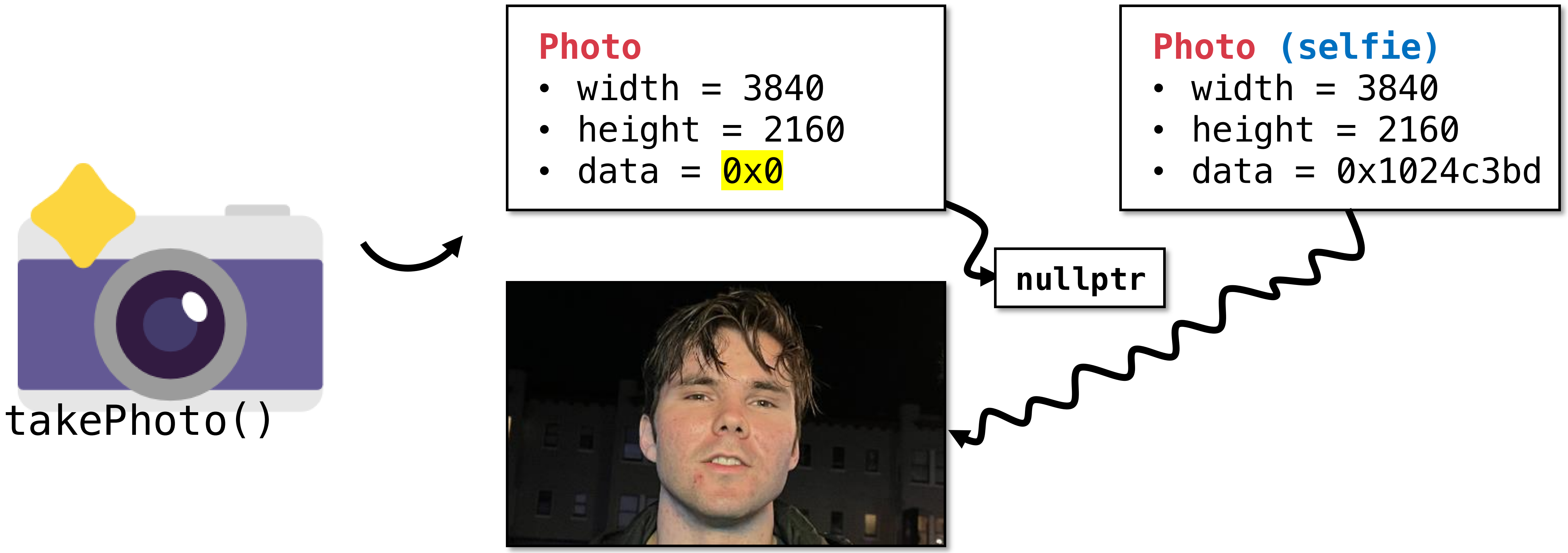


Photo
- width = 3840
- height = 2160
- data = 0x0

Photo (selfie)
- width = 3840
- height = 2160
- data = 0x1024c3bd

```
Photo selfie = takePhoto(); // ~~Copy~~ Move constructor
```

The Problem

takePhoto()

```
☠ Photo
• width = 3840
• height = 2160
• data = 0x0
```

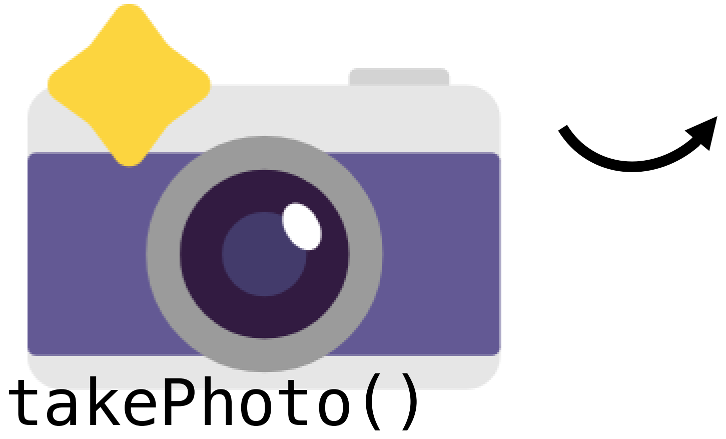
nullptr

```
Photo (selfie)
• width = 3840
• height = 2160
• data = 0x1024c3bd
```

Photo destructor calls delete on nullptr, which does nothing!

```
Photo selfie = takePhoto(); // Destructor
```

The Problem



☠ Photo
- width = 3840
- height = 2160
- data = 0x0

nullptr

Photo (selfie)
- width = 3840
- height = 2160
- data = 0x1024c3bd

```
Photo selfie = takePhoto(); // Destructor
```

We created a new Photo without any copying! 💪

But… is it always safe to do this?

Move vs. Copy Semantics

`takePhoto()` is temporary, so we can steal its resources!

```
Photo takePhoto();

int main() {
  Photo selfie = takePhoto(); // Move takePhoto()
                             // since it’s temporary!
}
```

Move vs. Copy Semantics

Is it always safe to move objects? Assume `get_pixel` accesses data

```
Photo takePhoto();

void foo(Photo whoAmI) {
   Photo selfie = whoAmI;      // What if we move here?
   whoAmI.get_pixel(21, 24);   // ???
}
```

What will happen if we try to run this code?

Move vs. Copy Semantics

❌ Since `selfie` stole `whoAmI`'s data, we end up dereferencing `nullptr`

```cpp
Photo takePhoto();

void foo(Photo whoAmI) {
   Photo selfie = whoAmI;      // What if we move here?
   whoAmI.get_pixel(21, 24);   // ❌ use-after-move
}
```

Move vs. Copy Semantics

```
Photo selfie = pic;
// make copies of persistent objects (e.g. variables)
// that might get used in the future

Photo selfie = takePhoto();
// move temporary objects (e.g return values)
// since we no longer need to use them
```

What questions do you have?

`bjarne_about_to_raise_hand`

Move vs. Copy Semantics

```
Photo selfie = pic;
// make copies of persistent objects (e.g. variables)
// that might get used in the future

Photo selfie = takePhoto();
// move temporary objects (e.g return values)
// since we no longer need to use them


How does the compiler know whether to move or copy?
```

lvalues & rvalues

lvalues & rvalues

lvalues and rvalues generalize the idea of “temporariness” in C++

```
void foo(Photo pic) {
  Photo beReal = pic;
  Photo insta = takePhoto();
}
```

`pic` is an lvalue!

`takePhoto()` is an rvalue!

lvalues & rvalues

Generally speaking, **lvalues** have a definite address, **rvalues** do not!

```cpp
void foo(Photo pic) {
  Photo* p1 = &pic;
  Photo* p2 = &takePhoto(); // ❌ Doesn't work!
}
```

pic is an lvalue!

We can take its address!

takePhoto() is an rvalue!

We **cannot** take its address!

An lvalue can appear on either side of an =

```
x = y;
y = 5;
```

An rvalue can appear only right of an =

```
x = 5;
~~5 = y;~~
```

Your Turn

Which of the following right-hand assignments are rvalues?

- Hint: which ones have a definite address?

```
int           a = 4;                        rvalue
int&          b = a;                        lvalue
vector<int>   c = {1, 2, 3};                rvalue
int           d = c[1];                     lvalue
int*          e = &c[2];                    rvalue
size_t        f = c.size();                 rvalue
int           g = static_cast<int>(f);      lvalue
```

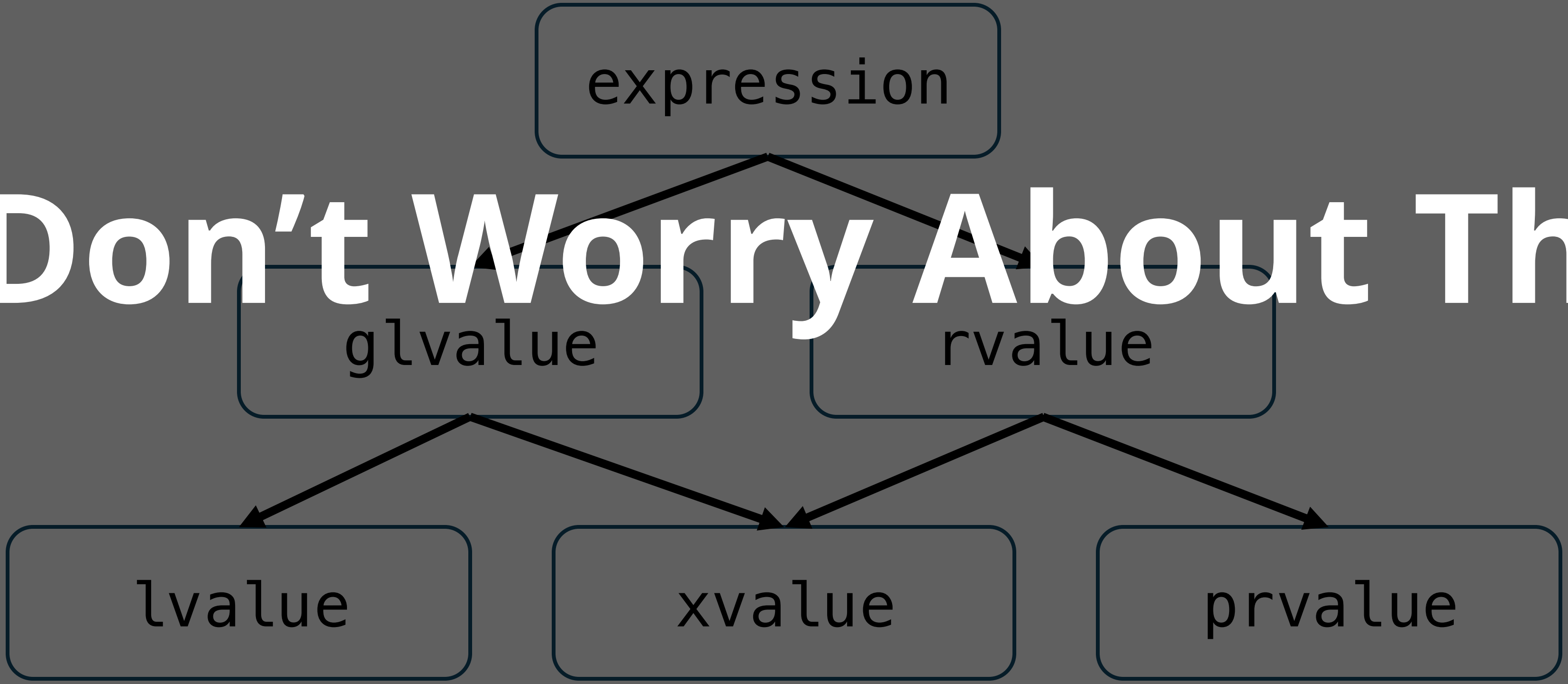
An lvalue's lifetime is until the end of scope

An rvalue's lifetime is until the end of line

An lvalue is persistent

An rvalue is temporary

Quick Note: It’s more complicated than this!



❌ Don’t Worry About This

Working towards move semantics

If we have an `lvalue`, how can we avoid copying its memory?

```
void uploadToInsta(Photo pic);

int main() {
  Photo selfie = takePhoto(); // selfie is lvalue
  uploadToInsta(selfie); // 🤦 Unnecessary copy is made here
}
```

Working towards move semantics

We can pass by reference! 🥳

```
void uploadToInsta(Photo& pic);

int main() {
  Photo selfie = takePhoto(); // selfie is lvalue
  uploadToInsta(selfie); // ✅ No copy is made here
}
```

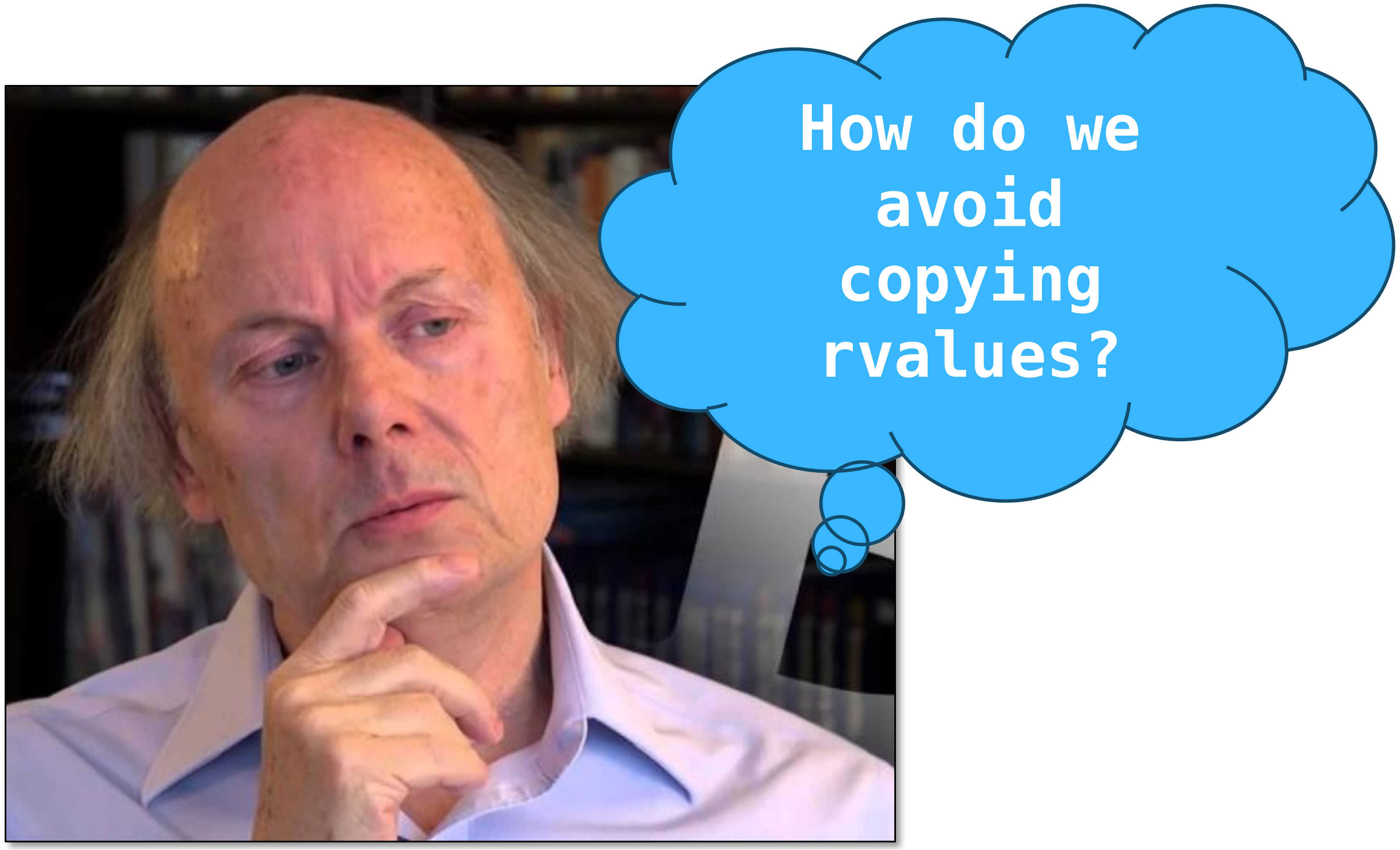
Working towards move semantics

- How can we avoid copying **rvalues**?
- What happens if we try to pass by reference?

```
void uploadToInsta(Photo& pic);

int main() {
  uploadToInsta(takePhoto()); // Does this work?
}
```

❌ `candidate function not viable: expects lvalue as 1st argument`



thinking_bjarne

lvalue reference

```
void upload(Photo& pic);

int main() {
  Photo selfie = takePhoto();
  upload(selfie);
}
```

rvalue reference

```
void upload(Photo&& pic);

int main() {
  upload(takePhoto());
}
```

We can do whatever we want with **Photo&&** pic, it's temporary!

A few important points

- **lvalue** references
  - Syntax: Type&
  - Persistent, must keep object in valid state after function terminates
- **rvalue** references
  - Syntax: Type&&
  - Temporary, we can steal (move) its resources
  - Object might end up in an invalid state, but that’s okay! It’s temporary!

```cpp
//Hello. I want to take your Widget and play with it. It may be in a
//different state than when you gave it to me, but it'll still be yours
//when I'm finished. Trust me!
void foo(Widget& w);
```

```cpp
//Hello. Ooh, I like that Widget you have. You're not going to use it
//anymore, are you? Please just give it to me. Thank you! It's my
//responsibility now, so don't worry about it anymore, m'kay?
void foo(Widget&& w);
```

[source]

Key Idea: Overloading & and && parameters distinguish lvalue and rvalue references

lvalue/rvalue overloading

```
void upload(Photo& pic);

int main() {
   Photo selfie = takePhoto();
   upload(selfie);
}
```

```
void upload(Photo&& pic);

int main() {
   upload(takePhoto());
}
```

Compiler decides which version of **upload** to call depending on whether argument is lvalue or rvalue!

What questions do you have?

bjarne_about_to_raise_hand

Move Semantics

What we want!

Photo&

```
Photo selfie = pic;
// copy persistent objects (e.g. variables)
```

Photo&&

```
Photo selfie = takePhoto();
// move temporary objects (e.g return values)
```

Let’s overload the special member functions!

Copy constructor

```
Photo::Photo(const Photo& other)
    : width(other.width)
    , height(other.height)
    , data(new int[width * height])
{
    std::copy(
        other.data,
        other.data + width * height,
        data
    );
}
```

Move constructor

```
Photo::Photo(Photo&& other)
: width(other.width)
, height(other.height)
{
   // other is temporary
   // Let’s steal its
   // resources since we know
   // it’s about to be gone!
}
```

Let’s overload the special member functions!

Copy assignment operator

```
Photo& Photo::operator=(const Photo& other) {
    if (this == &other) return *this;
    delete[] data;
    width = other.width;
    height = other.height;
    data = new int[width * height];
    std::copy(other.data, other.data +
    width * height, data);
    return *this;
}
```

Move assignment operator

```
Photo&
Photo::operator=(Photo&& other)
{
    // other is temporary
    // Let’s steal its
    // resources since we know
    // it’s about to be gone!
}
```

Let’s code this up!

Let’s code this together 👫

`106l.vercel.app/movesem`

Two new special member functions!

- Move constructor
  - `Type::(Type&& other)`
- Move assignment operator
  - `Type& Type::operator=(Type&& other)`

What questions do you have?

bjarne_about_to_raise_hand

`std::move` and SMFs

Forcing Move Semantics

- Usually, we let the compiler decide between & and &&
- Is that always the most efficient choice?
  - E.g. what if we know that an lvalue will never be used again?

Forcing Move Semantics

Line 3 *copies* each element into its new spot, even though the original value is never used again

```
1 void PhotoCollection::insert(const Photo& pic, int pos) {
2     for (int i = size(); i > pos; i--)
3         elems[i] = elems[i - 1]; // Shuffle elements down
4     elems[i] = pic;
5 }
```

Forcing Move Semantics

Solution: use move semantics

```
void PhotoCollection::insert(const Photo& pic, int pos) {
  for (int i = size(); i > pos; i--)
    elems[i] = std::move(elems[i - 1]);
  elems[i] = pic;
}
```

Be wary of `std::move`

If we move an lvalue, what happens to it afterwards?

```
Photo takePhoto();

void foo(Photo whoAmI)
   Photo selfie = std::move(whoAmI);
   whoAmI.get_pixel(21, 24); // ???
}
```

❌ If we move, `whoAmI` ends up in an unknown state!

Use `std::move` to implement move operations!

```
class Photo {
public:
  Photo::Photo(Photo&& other) {
    keywords = other.keywords;
  }

private:
  std::vector<string> keywords;
};
```

We know that `other` is temporary! So do we *really* need to make a copy of `other.keywords`?

Use std::move to implement move operations!

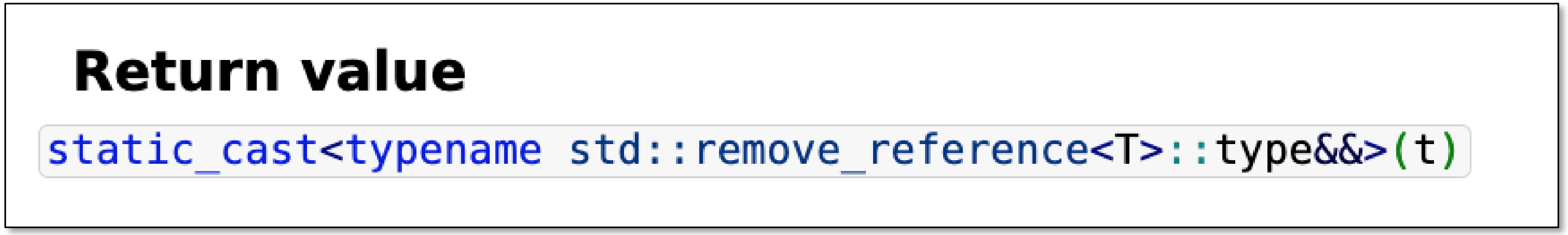
```
class Photo {
public:
   Photo::Photo(Photo&& other) {
      keywords = std::move(other.keywords);
   }

private:
   std::vector<string> keywords;
};
```

Solution: force move semantics by using std::move

`std::move` doesn't do anything special!

- `std::move` just type casts an lvalue to an rvalue



Return value

```
static_cast<typename std::remove_reference<T>::type&&>(t)
```

- Like `const_cast`, we "opt in" to potentially error-prone behaviour
  - What if we try to use an object after it's been moved! 🚨 🆘 🚨
- Try to avoid explicitly using `std::move` unless you have good reason!
  - E.g. performance really matters, you know for sure the object won't be used!

What questions do you have?

bjarne_about_to_raise_hand

We have two new SMFs!

- `Type::Type(const Type& other);`
- `Type& Type::operator=(const Type& other);`
- **`Type::Type(Type&& other);`**
- **`Type& Type::operator=(Type&& other);`**
- `~Type::Type();`

So many SMFs… 😩
Do I need to define them all!?

No! Rule of zero, three, and five!

Rule of Zero

- If a class doesn't manage memory (or another external resource), the compiler generated versions of the SMFs are sufficient!
- **Example:** Compiler generated SMFs of `Post` will call SMFs of `Photo` and `std::string`

```
struct Post {
    Photo photo;
    std::string user;
};
```

Rule of Three

- If a class manages external resources, we must define **copy assignment/constructor**
- If we don't, compiler-generated SMF won't copy underlying resource
  - This will lead to bugs, e.g. two `Photo`'s referring to the same underlying data

```
Rule of Three: If you need any one of these, you need them all:
    • Destructor
    • Copy Assignment
    • Copy Constructor
```

Rule of Five

- If we defined **copy constructor/assignment** and **destructor**, we should also define **move constructor/assignment**
- This is not required, but our code will be slower as it involves unnecessary copying

```
Rule of Five: If you need any of these, you probably want them all:
    •  Destructor
    •  Copy Assignment
    •  Copy Constructor
    •  Move Assignment    (Optional)
    •  Move Constructor   (Optional)
```

What questions do you have?

`bjarne_about_to_raise_hand`