Welcome back! Link to Attendance Form ↓

https://forms.gle/EDvaPayzm4T8i9pS6


Low Battery
10% battery remaining.
Low Power Mode
Close

Things that drain battery life

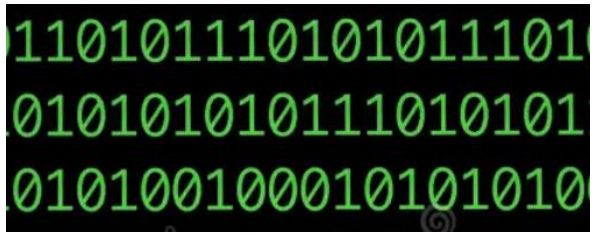
Connecting to WiFi

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]


ME WHEN MY PHONE IS
DEAD AND I HAVE NOTHING TO DO
imgflip.com

Why does it matter?

How can we avoid needlessly copying data?

Lecture 14: Move Semantics

CS106L, Fall 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 photo(500, 500);
```

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 p = photo;
```

Photo SMF: Copy Assignment

```
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;
}
```

E.g. if we did

p = p;

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

p = photo;

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)
    Photo retake(0, 0);
    retake = takePhoto();                // (B)
}
```

Copy **Destruct**

Assign **Destruct**

A Small Aside: Return Value Optimization

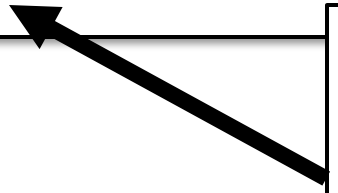
- This line

```
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();
```



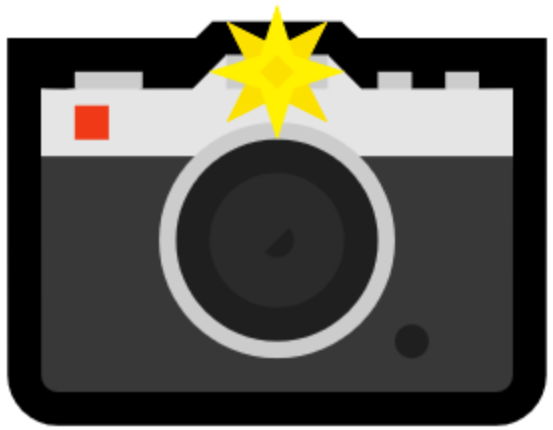
The compiler is going to clean this object up before moving onto the next line!

What questions do you have?

bjarne_about_to_raise_hand

The Problem

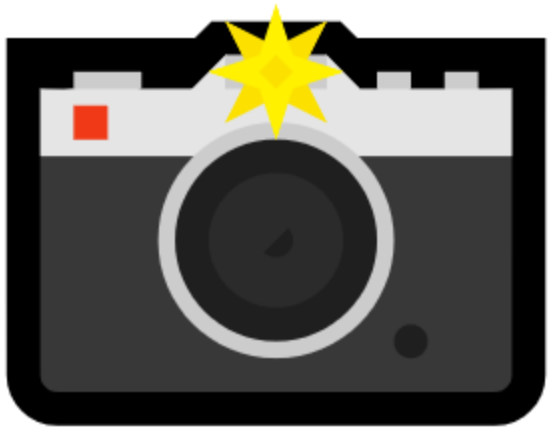
The Problem



takePhoto()

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

The Problem

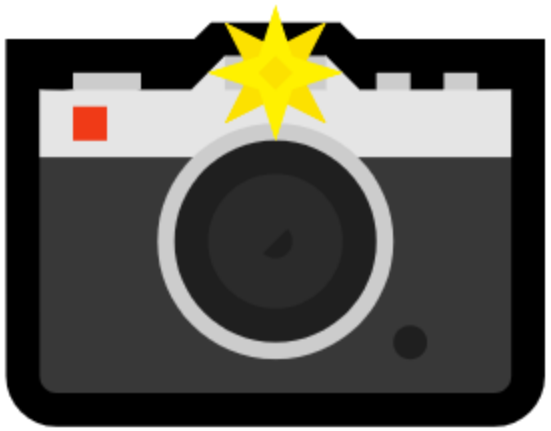


takePhoto()

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

Photo selfie = takePhoto();

The Problem



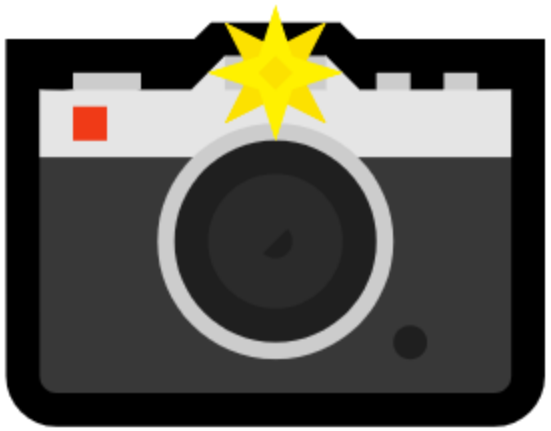
takePhoto()

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

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

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

The Problem



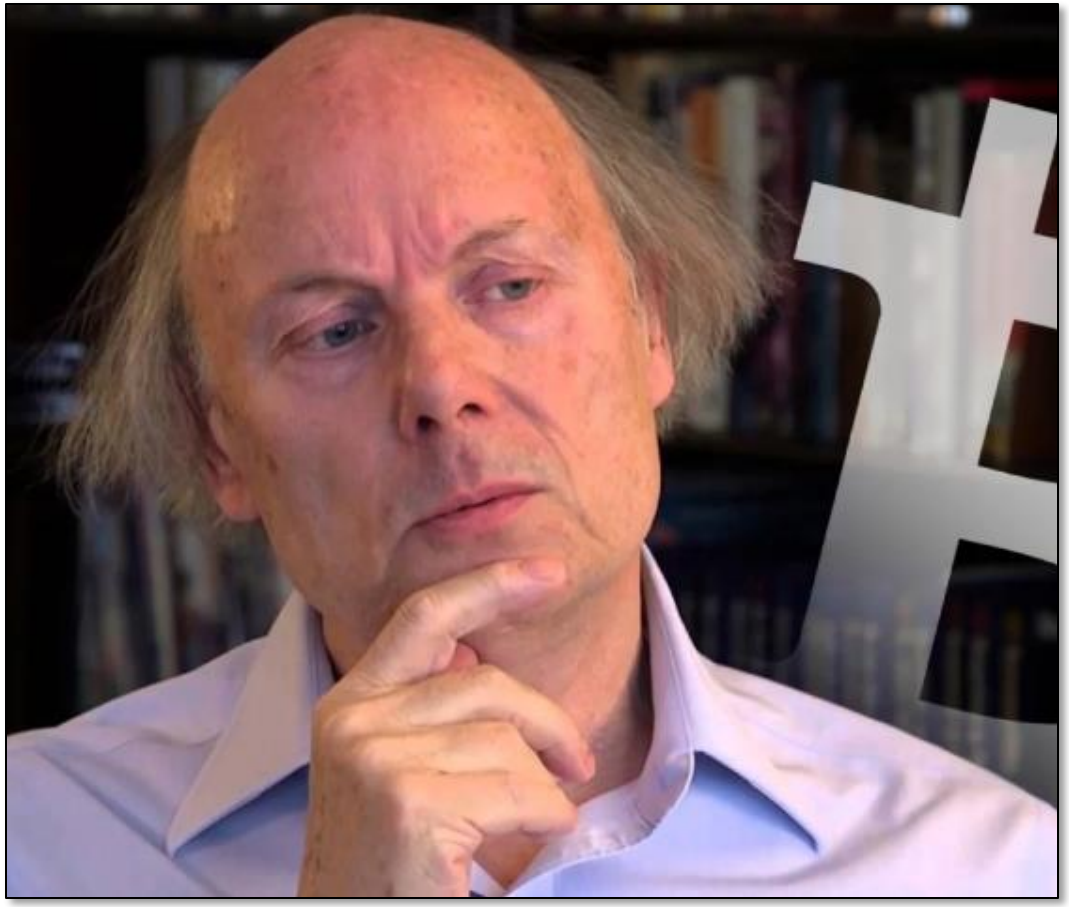
takePhoto()

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

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

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

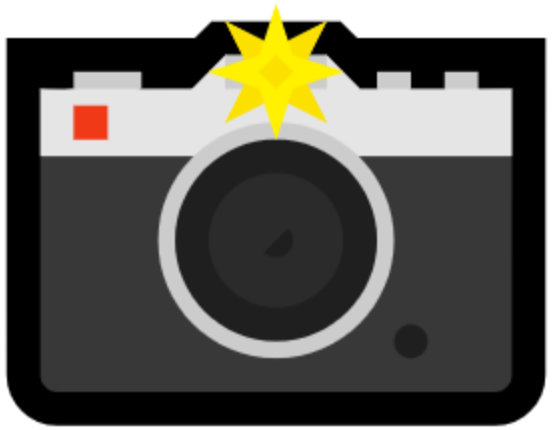
The Problem



concerned_bjarne

What if we could reuse the memory instead?

The Solution: Move Semantics

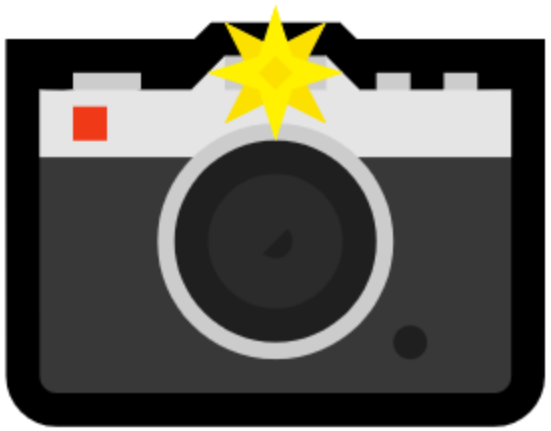


takePhoto()

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

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

The Problem



takePhoto()

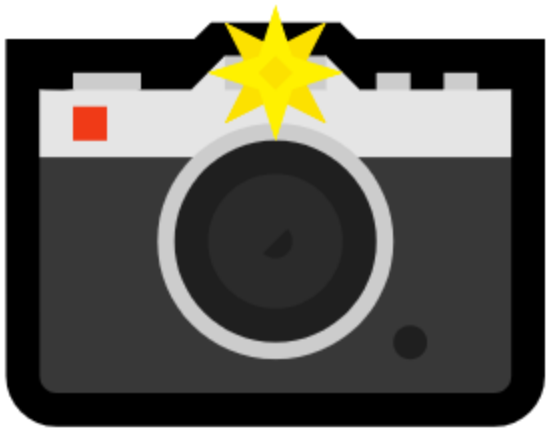
Photo
- width = 3840
- height = 2160
- data = 0x1024c3bd

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

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

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

The Problem



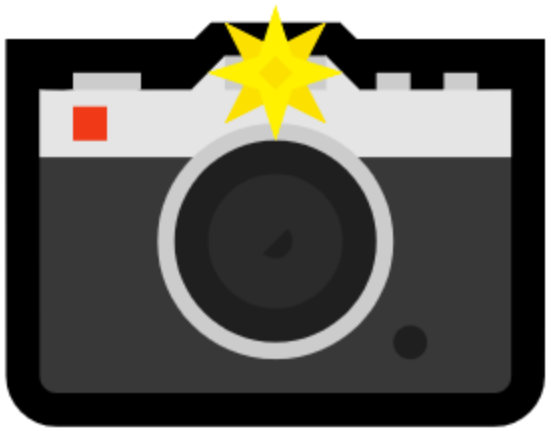
takePhoto()

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

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

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

The Problem



takePhoto()

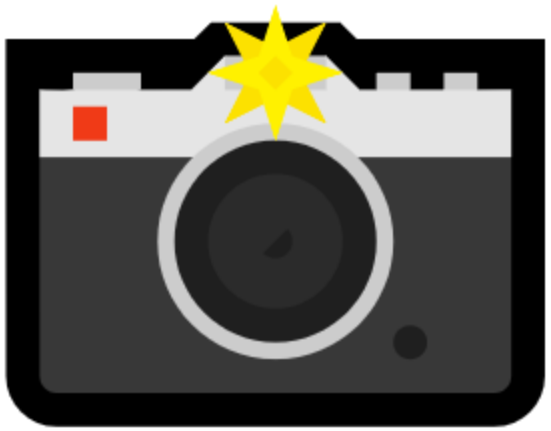
Photo
- width = 3840
- height = 2160
- data = 0x1024c3bd

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

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

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

The Problem



takePhoto()

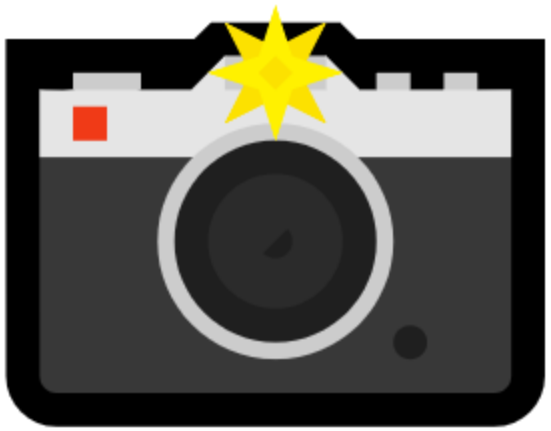
Photo
- width = 3840
- height = 2160
- data = 0x0

nullptr

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

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

The Problem



takePhoto()

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

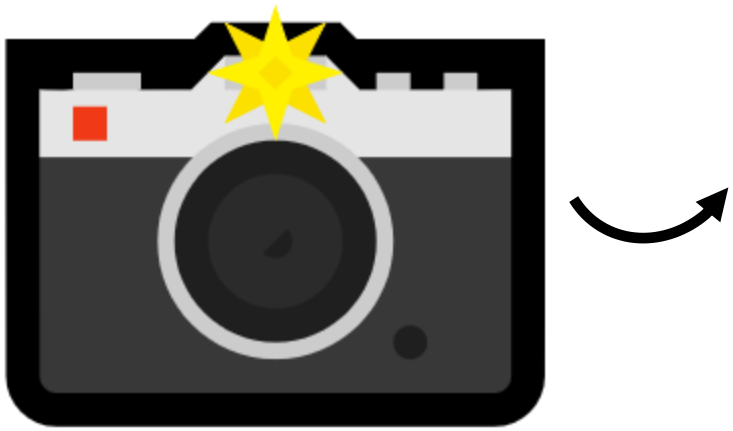
nullptr

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

Photo destructor calls delete on nullptr, which does nothing!

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

The Problem



takePhoto()

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

```
Photo takePhoto();

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

Building a new computer

Copy semantics

“I still want to use my old computer”

Move semantics

“I don’t need my old computer”

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
```

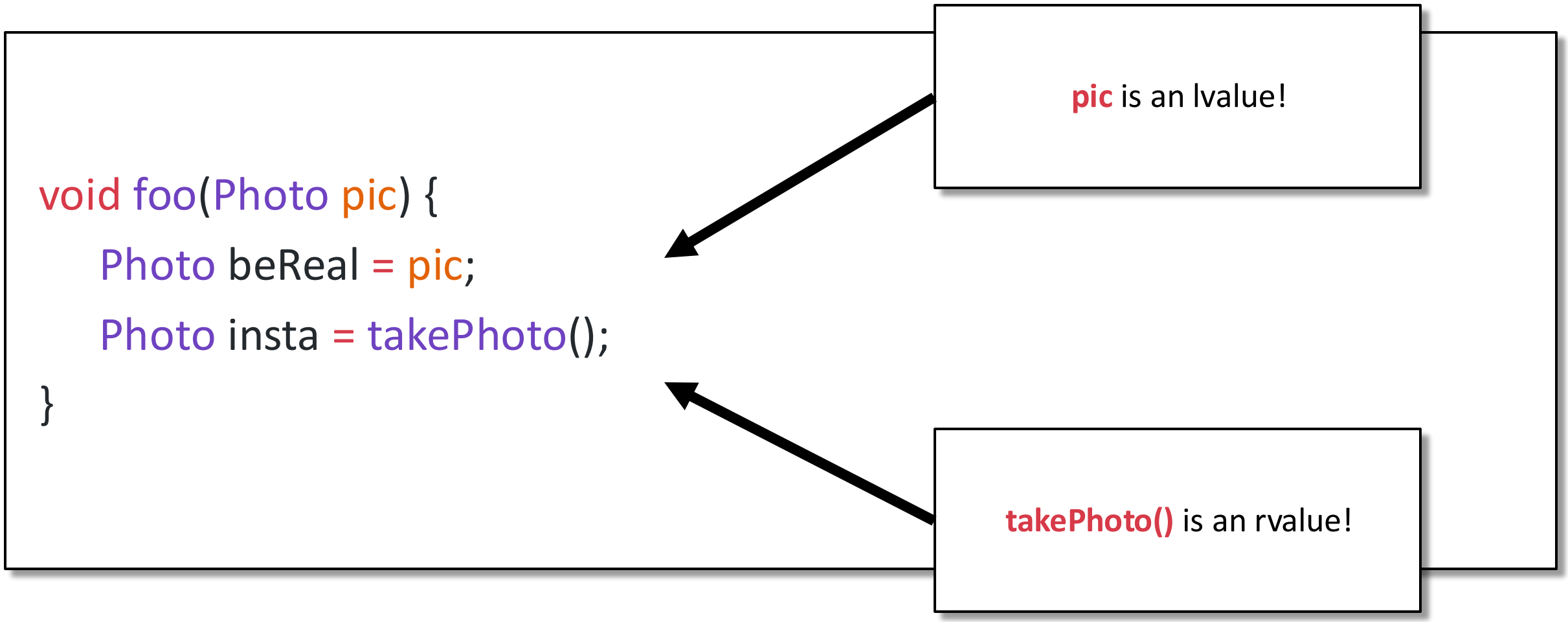
How does the compiler know whether to move or copy?

lvalues & rvalues

lvalues & rvalues

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

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



lvalues & rvalues

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

```
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
```

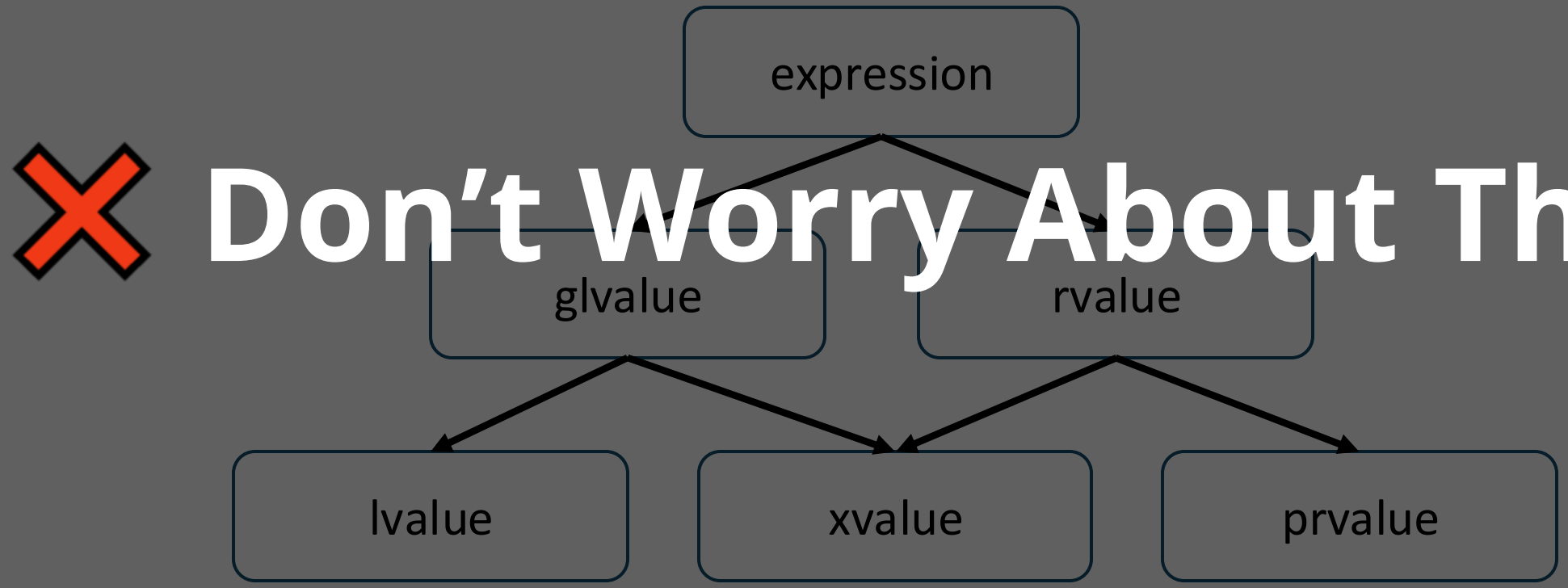
An lvalue's lifetime is until the end of scope

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
}
```

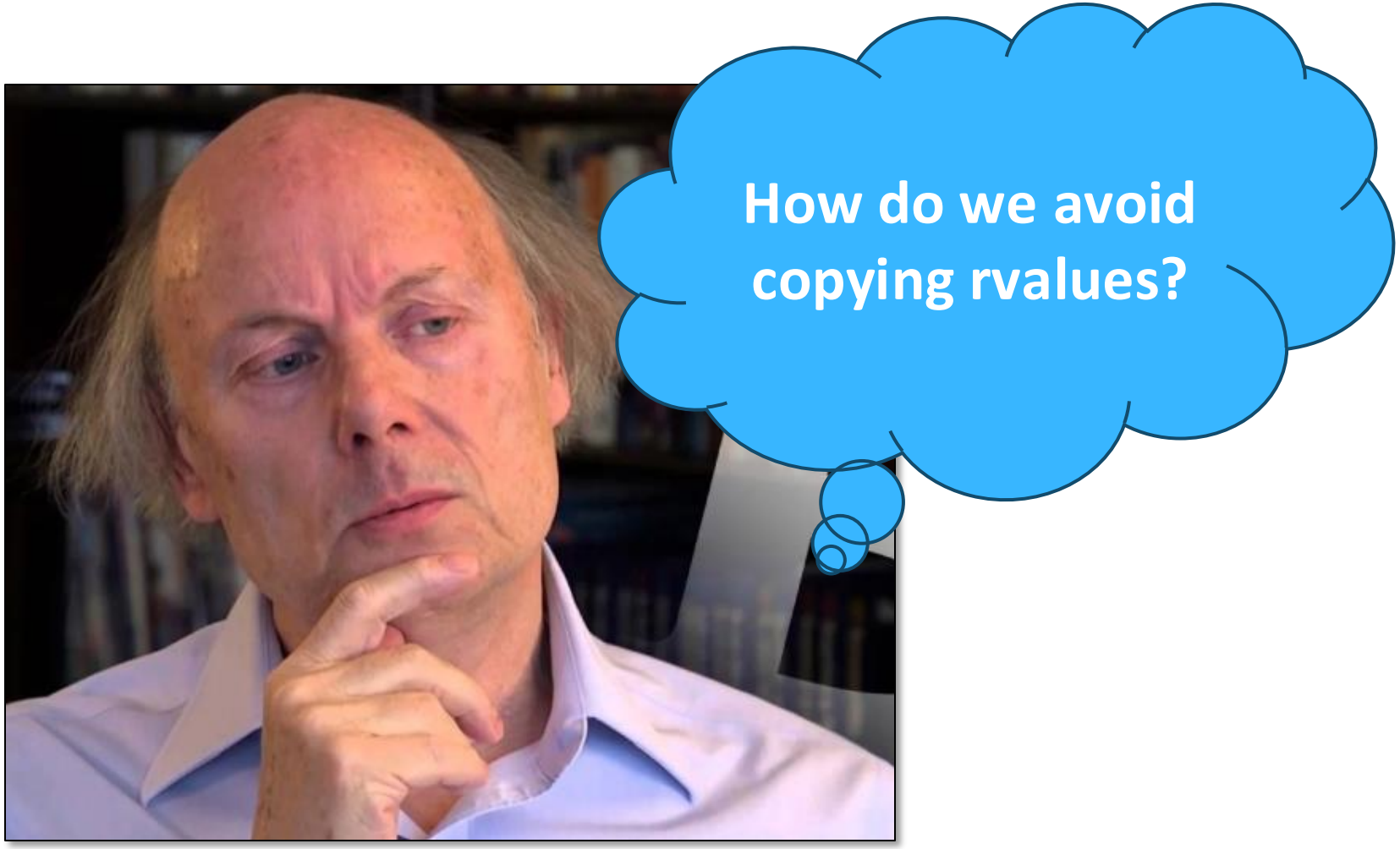
Working towards move semantics

- 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!

```
//Here are the keys to my car as long as you promise to not give it a
//paint job or anything like that
void foo(const Car& c);

//I don't need my car anymore, so I'm signing the title over to you now.
//Happy birthday!
void foo(Car&& c);
```

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


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

Two new special member functions!

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

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 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)
, data(other.data)
{
        other.data = nullptr;
}
```

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 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)
{
        if (this == &other) return *this;
        delete[] data
        width = other.width
        height = other.height
        data = other.data
        other.data = nullptr;
        return *this;
}
```

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           myPhotos[i] = myPhotos[i – 1]; // Shuffle elements down
4       myPhotos[i] = pic;
5   }
```

Forcing Move Semantics

Solution: use move semantics

```
1   void PhotoCollection::insert(const Photo& pic, int pos) {
2       for (int i = size(); i > pos; i--)
3           myPhotos[i] = std::move(myPhotos[i – 1]);
4       myPhotos[i] = pic;
5   }
```

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!

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!

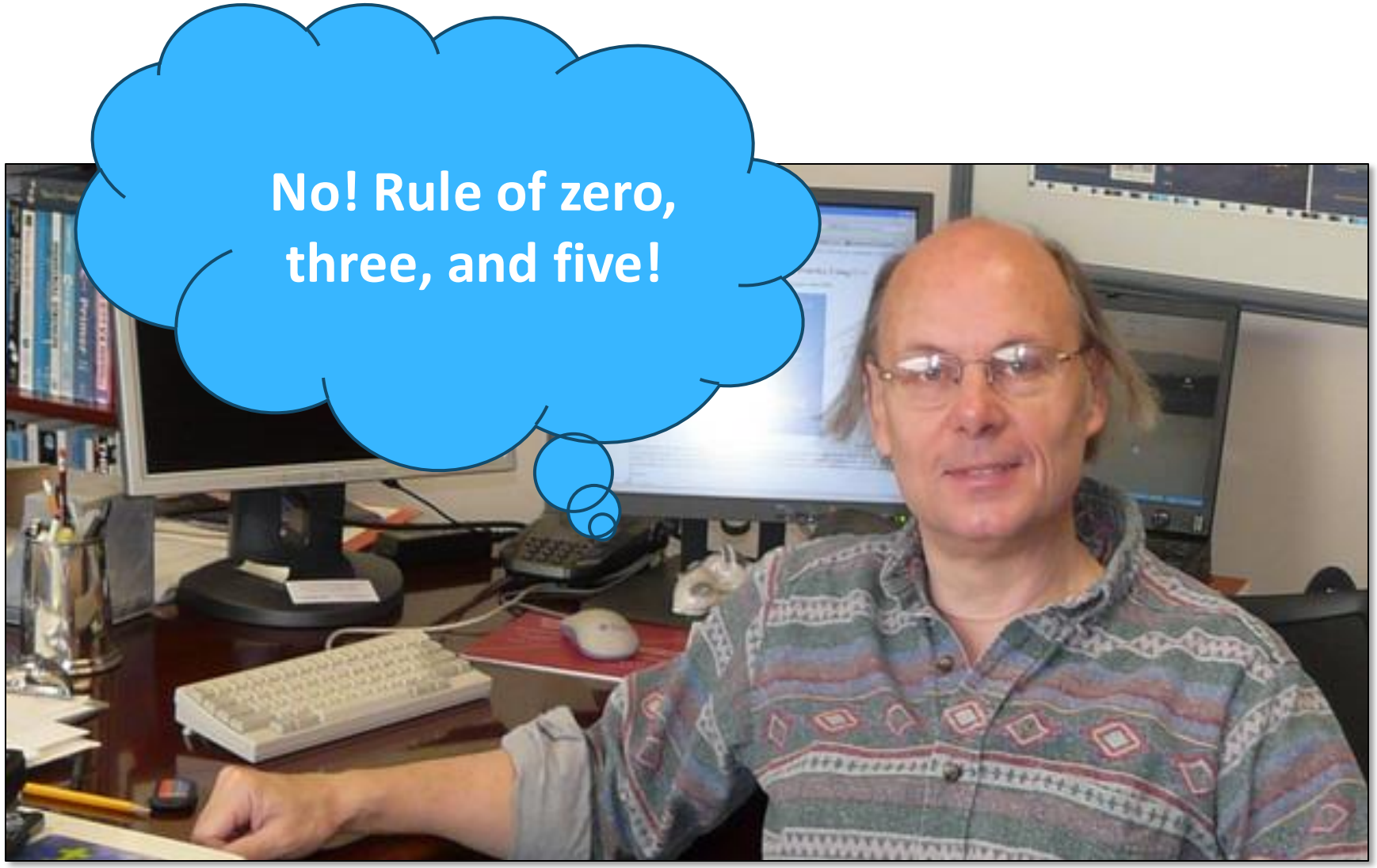
What questions do you have?

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 caption;
};
```

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