RAII

- Resource Acquisition Is Initialization
- The idea: keep a resource is expressed by object lifetime

```
// is this correct?
void f()
{
    char *cp = new char[1024];

    g(cp);
    h(cp);

    delete [] cp;
}
```

RAII

- Resource Acquisition Is Initialization
- The idea: keep a resource is expressed by object lifetime

```
// is this maintainable?
void f()
{
    char *cp = new char[1024];

    try
    {
      g(cp);
      h(cp);
      delete [] cp;
    }
    catch (...)
    {
      delete [] cp;
      throw;
    }
}
```

RAII

- Constructor allocates resource
- Destructor deallocates

```
// RAII
struct Res
{
    Res(int n) { cp = new char[n]; }
    ~Res() { delete [] cp; }
    char *getcp() const { return cp; }
};

void f()
{
    Res res(1024);

    g(res.getcp());
    h(res.getcp());
}
// resources will be freed here
```

RAII

- Constructor allocates resource
- Destructor deallocates

```
// RAII
struct Res
{
    Res(int n) { cp = new char[n]; }
    ~Res() { delete [] cp; }
    char *getcp() const { return cp; }
};  // Copy? Move?

void f()
{
    Res res(1024);

    g(res.getcp());
    h(res.getcp());
}
// resources will be freed here
```

RAII

- Should be careful when implementing RAII
- Destructor calls only when living object goes out of scope
- Object lives only when constructor has successfully finished

```
// But be careful:
struct BadRes
{
    Res(int n) { cp = new char[n]; ... init(); ... }
    ~Res()     { delete [] cp; }
    char *cp;
    void init()
    {
       /* ... */  if (error) throw XXX;  /* ... */
    }
};
```

Smart pointers

- The deprecated auto pointer
- How smart pointers work?
- Unique_ptr
- Shared_ptr and weak_ptr
- Make_ functions
- Shared pointer from this
- Traps and pitfalls

How to handle ownership?

- Owner
  - Responsible releasing the resource
    - Single owner
    - Reference counting
  - Examples
    - Memory std::vector<>, std::array<>, std::shared_ptr<>, std::string
    - std::lock_guard<>
    - std::ifstream
- Observer
  - Examples
    - std::weak_ptr<>
    - std::string_view<>

Auto_ptr

- The only smart pointer in C++98/03
- Cheap, ownership-based
- Not works well with STL containers and algorithms
- Not works with arrays
- Deprecated in C++11
- Removed from C++ since C++17

Unique_ptr

- Single ownership pointer (similar to auto_ptr)
- Carefully designed to work with STL and other language features
- Movable but not copyable
- Deleter is type parameter – cannot be changed in run-time

```
#include <memory>
template< class T, class Deleter = std::default_delete<T>>
class unique_ptr;

template <class T, class Deleter>
class unique_ptr<T[],Deleter>;

void f()
{
  std::unique_ptr<MyClass>   up1(new MyClass());  // * and ->
  std::unique_ptr<MyClass[]> up2(new MyClass[n]); // []
  ...
}  // proper delete called here
```

Unique_ptr

```
#include <memory>

void f()
{
  std::unique_ptr<Foo> up(new Foo{});  // up is the only owner
  std::unique_ptr<Foo> up2(up);// compile error: can't copy unique_ptr
  std::unique_ptr<Foo> up3;    // nullptr: not owner
  const std::unique_ptr<Foo> up4(new Foo{}); // const pointer

  up3 = up;              // compile error: can't assign unique_ptr
  up3 = std::move(up);   // ownership moved to up3
  up3 = std::move(up4); // compile error: const can’t move

  std::vector<unique_ptr<int>> vi;
  vi.push_back(std::make_unique<int>(42));

} // vi destroyed:  int{42} is destroyed
  // up4 destroyed: Foo object is destructed
  // up3 destroyed: Foo object is destructed
  // up  destroyed: nop
```

How inheritance is implemented?

- Raw pointers: assign Derived* to Base* works
- But unique_ptr<Derived> is not inherited from unique_ptr<Base>
- The deleter is not copied – different from shared_ptr !!!

```
template<class T, class D>
class unique_ptr
{
private:
  T* ap;    // refers to the actual owned object (if any)
public:
  typedef T element_type;

  explicit unique_ptr (T* ptr = 0) : ap(ptr) { }
  unique_ptr (unique_ptr&& rhs) : ap(rhs.release()) { }
  template<class Y> unique_ptr(unique_ptr<Y>&& rhs):ap(rhs.release()){}

  unique_ptr& operator=(unique_ptr&& rhs) { ... }
  template<class Y,class D>
  unique_ptr& operator=(unique_ptr<Y,D>&& rhs) { ... }
};
```

Polymorphism

```
struct Base {
  virtual void f() { std::cout << "Base::f\n"; }
          ~Base()  { std::cout << "Base::~Base()\n"; }
};
struct Derived : Base {
  virtual void f() override   { std::cout << "Derived::f\n"; }
          ~Derived()          { std::cout << "Derived::~Derived()\n"; }
};

void g() {
  auto dp = std::make_unique<Derived>(); // std::unique_ptr<Derived>
  std::unique_ptr<Base> bp = std::move(dp);

  std::vector<std::unique_ptr<Base>> v;
  v.push_back(std::make_unique<Base>());
  v.push_back(std::make_unique<Derived>());
  for ( auto& p : v )  p->f();
};
```

Polymorphism

```
struct Base {
  virtual void f() { std::cout << "Base::f\n"; }
          ~Base()  { std::cout << "Base::~Base()\n"; }
};
struct Derived : Base {
  virtual void f() override   { std::cout << "Derived::f\n"; }
          ~Derived()          { std::cout << "Derived::~Derived()\n"; }
};

void g() {
  auto dp = std::make_unique<Derived>();
  std::unique_ptr<Base> bp = std::move(dp);

  std::vector<std::unique_ptr<Base>> v;
  v.push_back(std::make_unique<Base>());
  v.push_back(std::make_unique<Derived>());
  for ( auto& p : v )  p->f();
};

Base::f        // v[1] is Base
Derived::f     // v[2] is Derived
Base::~Base()  // oops v[2] is Derived  during destruction of v
Base::~Base()  // ok   v[1] is Base     during destruction of v
Base::~Base()  // oops                         delete bp
```

Polymorphism

```
struct Base {
  virtual void f() { std::cout << "Base::f\n"; }
  virtual ~Base()  { std::cout << "Base::~Base()\n"; }
};
struct Derived : Base {
  virtual void f() override   { std::cout << "Derived::f\n"; }
  virtual ~Derived() override { std::cout << "Derived::~Derived()\n"; }
};

void g() {
  auto dp = std::make_unique<Derived>();
  std::unique_ptr<Base> bp = std::move(dp);  // deleter is not copied

  std::vector<std::unique_ptr<Base>> v;
  v.push_back(std::make_unique<Base>());
  v.push_back(std::make_unique<Derived>());  // deleter is not copied
  for ( auto& p : v )  p->f();
};

Base::f             // v[1] is Base
Derived::f          // v[2] is Derived
Base::~Base()       // base part of v[2] Derived
Derived::~Derived() // derived part of v[2] since virtual destructor
Base::~Base()       // v[1]
Derived::~Derived() // bp points to Derived with virtual destructor
Base::~Base()       // base part of *bp
```

Polymorphism – shared_ptr

```
struct Base {
  virtual void f() { std::cout << "Base::f\n"; }
  virtual ~Base()  { std::cout << "Base::~Base()\n"; }
};
struct Derived : Base {
  virtual void f() override   { std::cout << "Derived::f\n"; }
  virtual ~Derived() override { std::cout << "Derived::~Derived()\n"; }
};

void g() {
  auto dp = std::make_shared<Derived>();
  std::shared_ptr<Base> bp = std::move(dp);  // deleter is moved

  std::vector<std::shared_ptr<Base>> v;
  v.push_back(std::make_shared<Base>());
  v.push_back(std::make_shared<Derived>());  // deleter is copied
  for ( auto& p : v )  p->f();
};

Base::f             // v[1] is Base
Derived::f          // v[2] is Derived
Base::~Base()       // base part of v[2] Derived
Derived::~Derived() // derived part of v[2] since default_deleter<Derived>
Base::~Base()       // v[1]
Derived::~Derived() // bp has default_deleter<Derived>
Base::~Base()       // base part of *bp:
```

Default deleter empty base optimization

```
template<class _T, class _DeleterT = std::default_delete<_T>>
class unique_ptr
{
public:
  // public interface...
private:
  // using empty base class optimization to save space
  // making unique_ptr with default_delete the same size as pointer
  class _UniquePtrImpl : private _DeleterT
  {
  public:
    constexpr _UniquePtrImpl() noexcept = default;
    // some other constructors...
    deleter_type& _Deleter() noexcept  { return *this; }
    const deleter_type& _Deleter() const noexcept { return *this; }
    pointer& _Ptr() noexcept { return _MyPtr; }
    const pointer _Ptr() const noexcept { return _MyPtr; }
  private:
     pointer   _MyPtr;
  };
  _UniquePtrImpl   _MyImpl;
};
```

Abstract factory pattern

```
#include <memory>

class Base { ... };
class Derived1 : public Base { ... };
class Derived2 : public Base { ... };


template <typename... Ts>
std::unique_ptr<Base>  makeBase( Ts&&... params )  { ... }

void f() // client code:
{
  auto pBase = makeBase( /* arguments */ );
}
// destroy object
```

Abstract Factory Pattern

```
auto delBase = [](Base *pBase)
               {
                   makeLogEntry(pBase);
                   delete pBase;  // delete object
               };

template <typename... Ts>
std::unique_ptr<Base, decltype(delBase)>  makeBase( Ts&&... params)
{
  std::unique_ptr<Base, decltype(delBase)> pBase(nullptr, delBase);

  if ( /* Derived1 */ )
  {
    pBase.reset(new Derived1( std::forward<Ts>(params)...) );
  }
  else if ( /* Derived2 */ )
  {
    pBase.reset(new Derived2( std::forward<Ts>(params)...) );
  }
  return pBase;
}
```

Evaluation

- Can be used in standard containers when polymorphic use needed
- The sizeof(unique_ptr<>) is sizeof(raw pointer) + deleter size
- If deault_deleter is used, then no extra size penalty
- If no deleter state (e.g. lambda with no capture): + sizeof(funptr)
- If deleter with state, the size increases
- Prefer unique_ptr when possible
- No copy of deleter :(
- No downcast operation :(

Downcast unique_ptr

```
template<typename Derived, typename Base, typename Del>
std::unique_ptr<Derived, Del>
dynamic_unique_ptr_cast( std::unique_ptr<Base, Del>&& p )
{
  if(Derived *r = dynamic_cast<Derived *>(p.get()))
  {
    p.release();
    return std::unique_ptr<Derived, Del>(r,std::move(p.get_deleter()));
  }
  return std::unique_ptr<Derived, Del>(nullptr, p.get_deleter());
}
```

shared_ptr

- Shared ownership pointer with reference counter
- Copy constructible and assignable
- Array specializations (shared_ptr<T[ ]>) since C++17
- Deleter type parameter – “copied“

```
#include <memory>
template< class T, class Deleter = std::default_delete<T>>
class shared_ptr;

void f()
{
  std::shared_ptr<MyClass>   sp1(new MyClass()); // * and ->
  std::shared_ptr<MyClass>   sp2(new MyClass[n], // * and ->
              std::default_delete<MyClass[]>()); //    before C++17
  std::shared_ptr<MyClass[]> sp3(new MyClass[n]);// [] since C++17
  ...
}  // proper delete called here
```

shared_ptr array specializaton

- Array spec. calls delete[]
- Only [ ] operator, no * and ->
- No conversion from shared_ptr<Der[ ]> to shared_ptr<Base[ ]>

```
struct Base {
  virtual void f() { std::cout << "Base::f\n"; }
  ~Base()  { std::cout << "Base::~Base()\n"; }
};
struct Derived : Base {
  virtual void f() override { std::cout << "Derived::f\n"; }
  ~Derived()  { std::cout << "Derived::~Derived()\n"; }
};

int main() {
  std::shared_ptr<Derived[]> sp(new Derived[5]);
  std::shared_ptr<Base[]>    bp(sp);  // compile error
  auto p  = sp[0];
  auto d0 = *sp;   // compile error
}
```

shared_ptr

```
void f()
{
  std::shared_ptr<int> p1(new int{5});
  std::shared_ptr<int> p2 = p1; // now both own the memory.

  p1.reset(); // memory still exists, due to p2.
} // p2 out of scope: delete the memory, since no one else owns.
```

```
T* get() const noexcept;
T& operator*() const noexcept;
T* operator->() const noexcept;
T& operator[](idx) const noexcept; // returns get()[idx]
```

```
long use_count() const noexcept;
bool unique() const noexcept;
explicit operator bool() const noexcept;
```

weak_ptr

- Not owns the memory
- But part of the “sharing group”
- No direct operation to access the memory
- Can be converted to shared_ptr with lock()

```
long use_count() const noexcept;
bool expired() const noexcept;     // use_count() == 0

shared_ptr<T> lock() const noexcept;
// return expired() ? shared_ptr<T>() : shared_ptr<T>(*this)

void reset() noexcept;
```

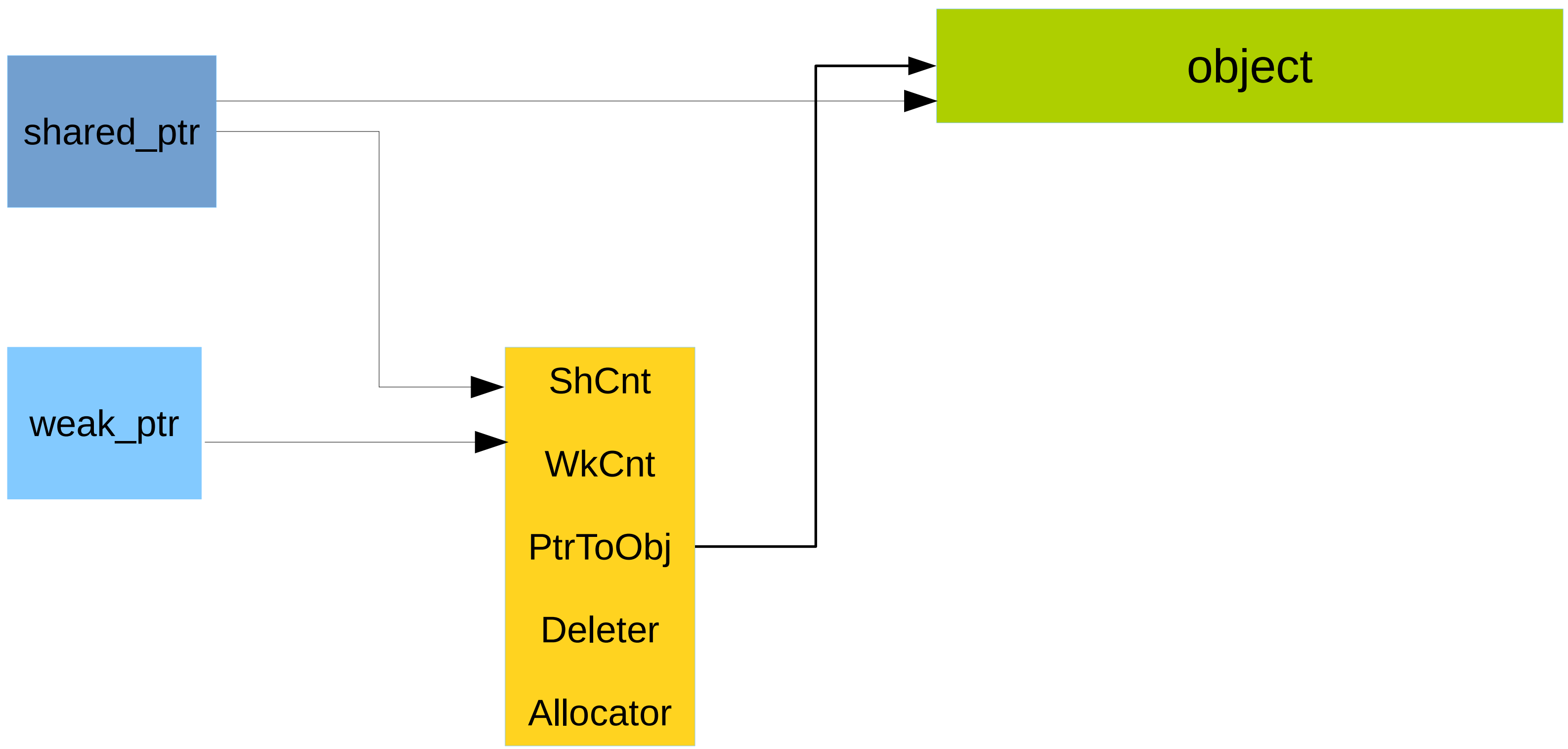
Using lock()

```
void f()
{
    std::shared_ptr<X> ptr1 = std::make_shared<X>();
    std::shared_ptr<X> ptr2 = ptr1;

    std::weak_ptr<X>   wptr = ptr2;

    if ( auto sp = wptr1.lock() )
    {
        // use sp
    } // destructor of sp called here: release X object
    else
    {
        // expired
    }
} // destructor of X object is called here
```

Using lock()

```
int main ()
{
  std::shared_ptr<int> sp1,sp2;
  std::weak_ptr<int>   wp;
                                      // sharing group:
                                      // --------------
  sp1 = std::make_shared<int> (20);   // sp1
  wp = sp1;                           // sp1, wp

  sp2 = wp.lock();                    // sp1, wp, sp2
  sp1.reset();                        //      wp, sp2

  sp1 = wp.lock();                    // sp1, wp, sp2
}
```

Typical shared_ptr implementation



Enable shared from this

```
#include <memory>
#include <cassert>

class Y
{
public:

    std::shared_ptr<Y> f()
    {
        return shared_ptr<Y>(this);  // ???
    }
};

int main()
{
    std::shared_ptr<Y> p(new Y);
    std::shared_ptr<Y> q = p->f();
    assert(p == q);
    assert(!(p < q || q < p));
}
```

Enable shared from this

```
#include <memory>
#include <cassert>

class Y
{
public:

    std::shared_ptr<Y> f()   // BAD!!!
    {
        return shared_ptr<Y>(this);  // ???
    }
};

int main()
{
    std::shared_ptr<Y> p(new Y);
    std::shared_ptr<Y> q = p->f();
    assert(p == q);                  // failes
    assert(!(p < q || q < p));       // failes
}
```

Enable shared from this

```
#include <memory>
#include <cassert>

class Y
{
public:
    Y() : ptr_to_me(std::shared_ptr<Y>(this)) { }
    std::shared_ptr<Y> f()
    {
        return ptr_to_me;  // ???
    }
private:
    std::shared_ptr<Y> ptr_to_me;
};

int main()
{
    std::shared_ptr<Y> p(new Y);
    std::shared_ptr<Y> q = p->f();
    assert(p == q);
    assert(!(p < q || q < p));
}
```

Enable shared from this

```
#include <memory>
#include <cassert>

class Y
{
public:
    Y() : ptr_to_me(std::shared_ptr<Y>(this)) { }
    std::shared_ptr<Y> f()  // BAD!!!
    {
        return ptr_to_me;  // ???
    }
private:
    std::shared_ptr<Y> ptr_to_me;
};

int main()
{
    std::shared_ptr<Y> p(new Y);
    std::shared_ptr<Y> q = p->f();
    assert(p == q);
    assert(!(p < q || q < p));
}
```

Enable shared from this

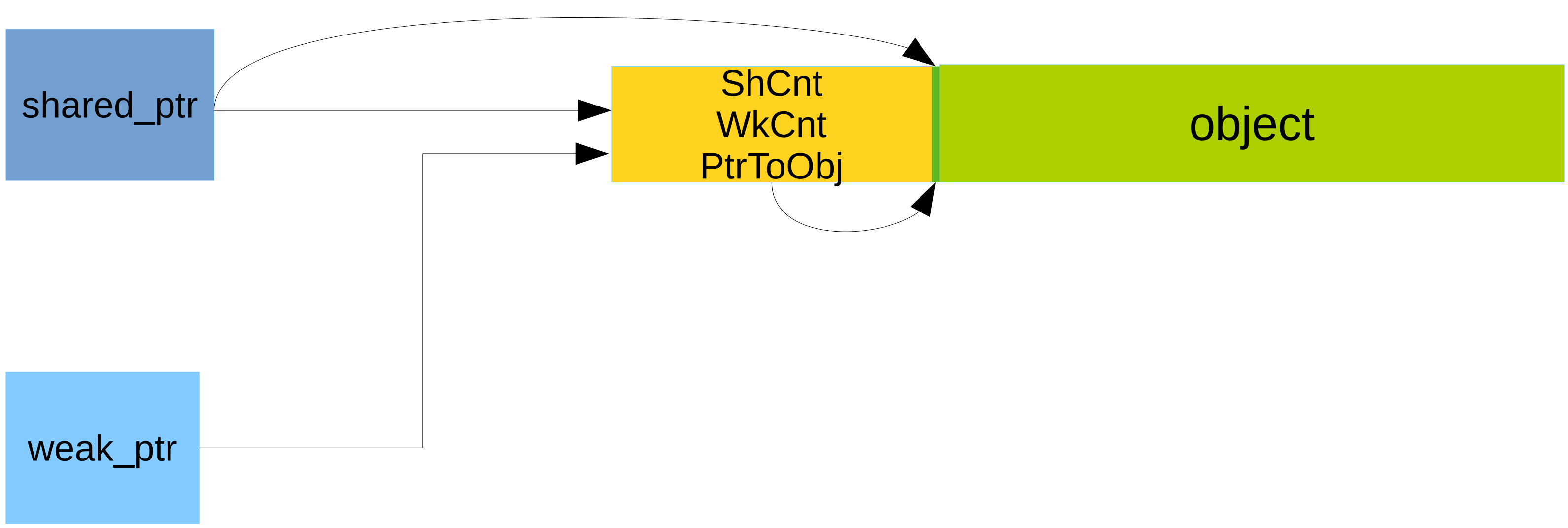
```
#include <memory>
#include <cassert>

class Y : public std::enable_shared_from_this<Y>
{
public:

    std::shared_ptr<Y> f()  // OK
    {
        return shared_from_this();
    }
};

int main()
{
    std::shared_ptr<Y> p(new Y);
    std::shared_ptr<Y> q = p->f();
    assert(p == q);
    assert(!(p < q || q < p)); // p and q share ownership
}
```

Make functions

```
// For unique_ptr
// default constructor of T
std::unique_ptr<T> v1 = std::make_unique<T>();
// constructor with params
std::unique_ptr<T> v2 = std::make_unique<T>(x,y,z);
// array of 5 elements
std::unique_ptr<T[]> v3 = std::make_unique<T[]>(5);

// similar methods for shared_ptr
```

Make functions

```
// For shared_ptr
// default constructor of T
std::shared_ptr<T> v1 = std::make_shared<T>();
// constructor with params
std::shared_ptr<T> v2 = std::make_shared<T>(x,y,z);
// array of 5 elements
std::shared_ptr<T[]> v3 = std::make_shared<T[]>(5);
```



Trap: exception safety

```
int f(); // may throw exception

// possible memory leak
std::pair<std::unique_ptr<MyClass>,int> foo()
{
  return std::make_pair(std::unique<MyClass>(new MyClass()), f());
}
```

Trap: exception safety

```
int f(); // may throw exception

// possible memory leak
std::pair<std::unique_ptr<MyClass>,int> foo()
{
  return std::make_pair(std::unique<MyClass>(new MyClass()), f());
}
```

1. Runs **new** MyClass
2. Runs f() and **throw** exception
3. std::unique_ptr constructor is not called

Trap: exception safety

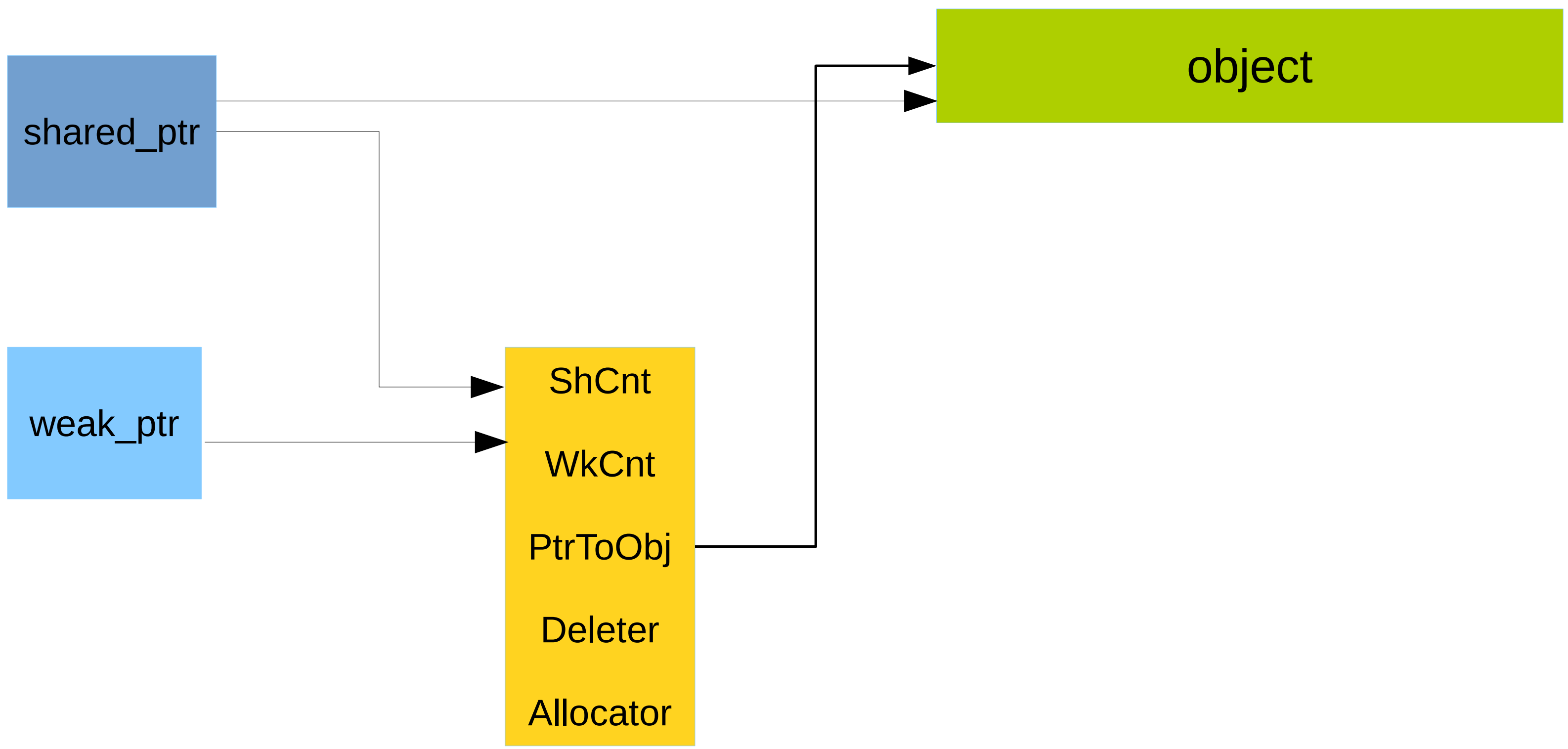
```
int f(); // may throw exception

// possible memory leak
std::pair<std::unique_ptr<MyClass>,int> foo()
{
  return std::make_pair(std::unique<MyClass>(new MyClass()), f());
}


int f(); // may throw exception

// safe
std::pair<std::unique_ptr<MyClass>,int> foo()
{
  return std::make_pair(std::make_unique<MyClass>(), f());
}
```

Trap: exception safety

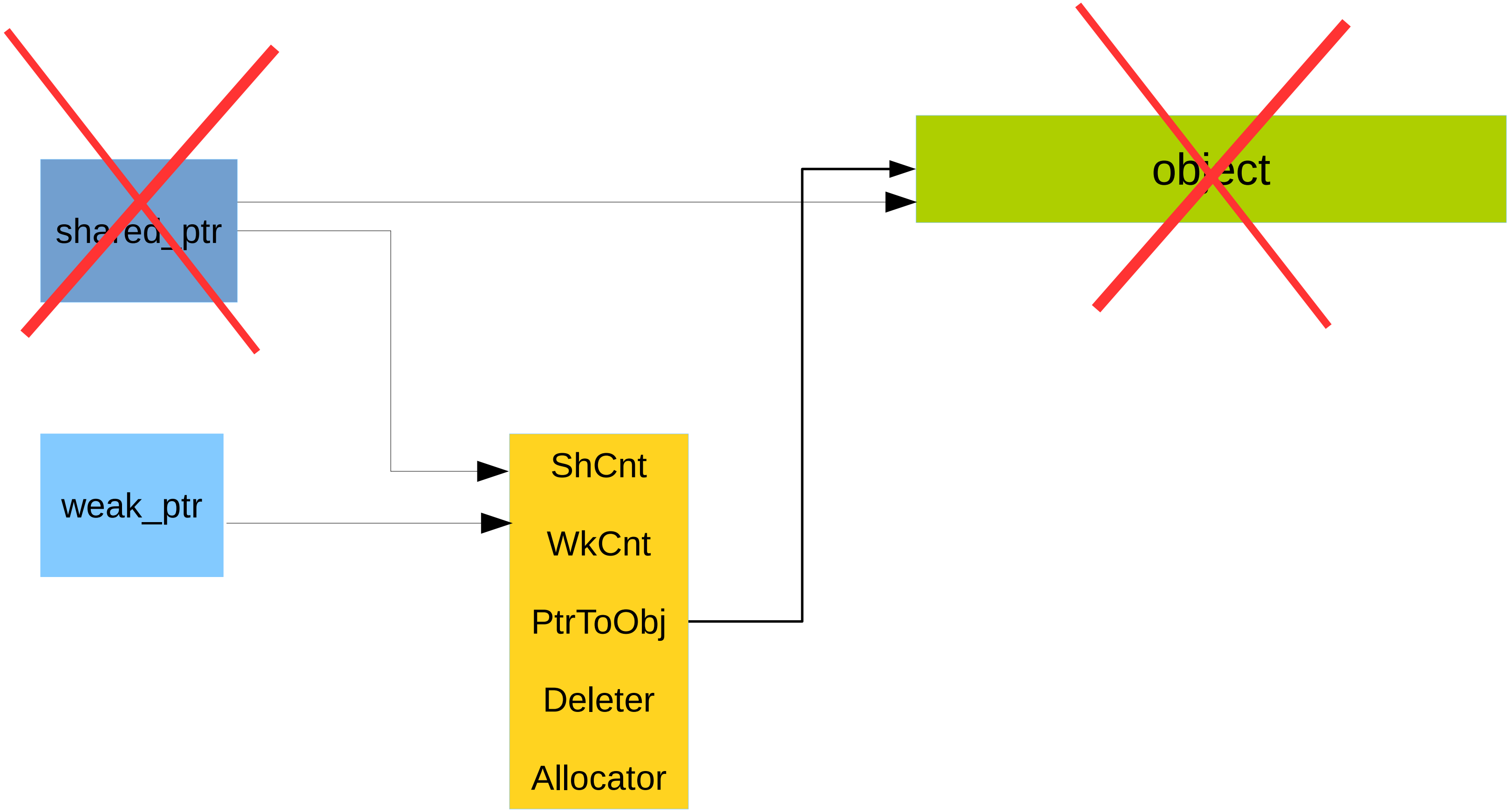
```cpp
int f(); // may throw exception

// possible memory leak
std::pair<std::unique_ptr<MyClass>,int> foo()
{
  return std::make_pair(std::unique<MyClass>(new MyClass()), f());
}


int f(); // may throw exception

// safe
std::pair<std::unique_ptr<MyClass>,int> foo()
{
  return std::make_pair(std::make_unique<MyClass>(), f());
}
```

No news – good news!

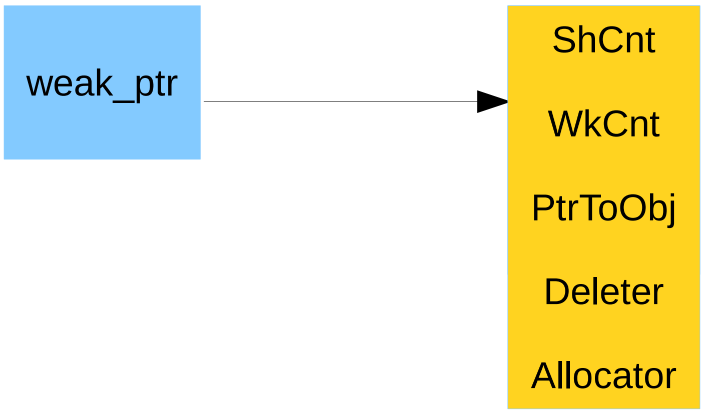
Trap: overuse of memory



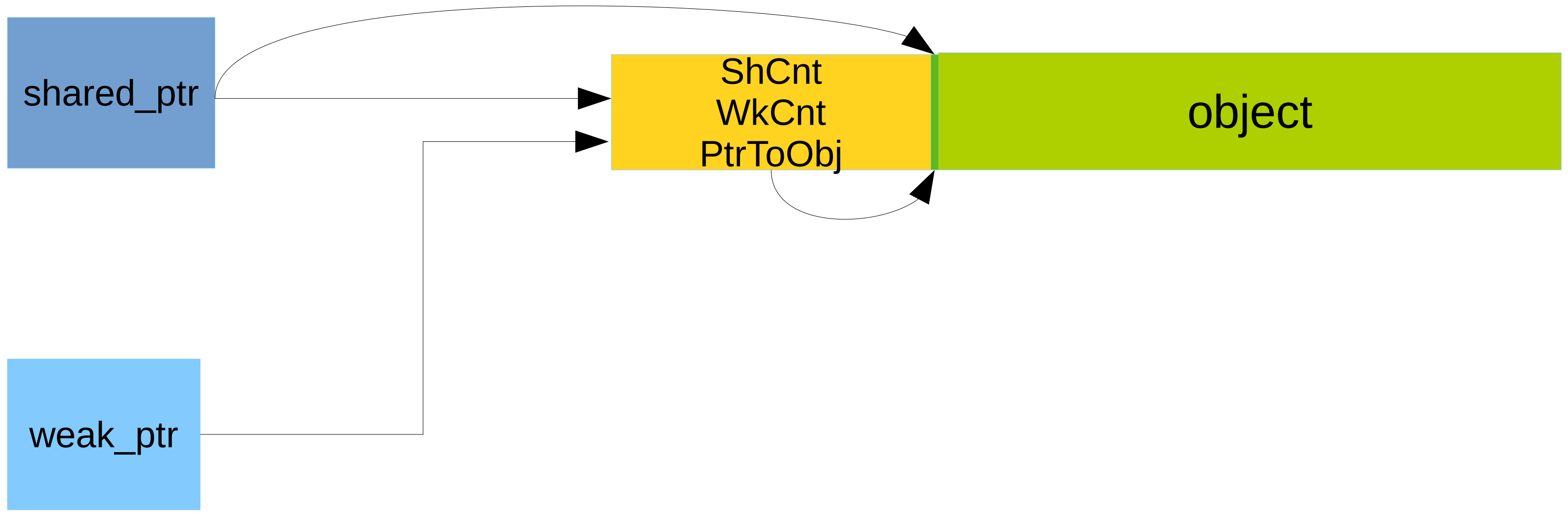
Trap: overuse of memory



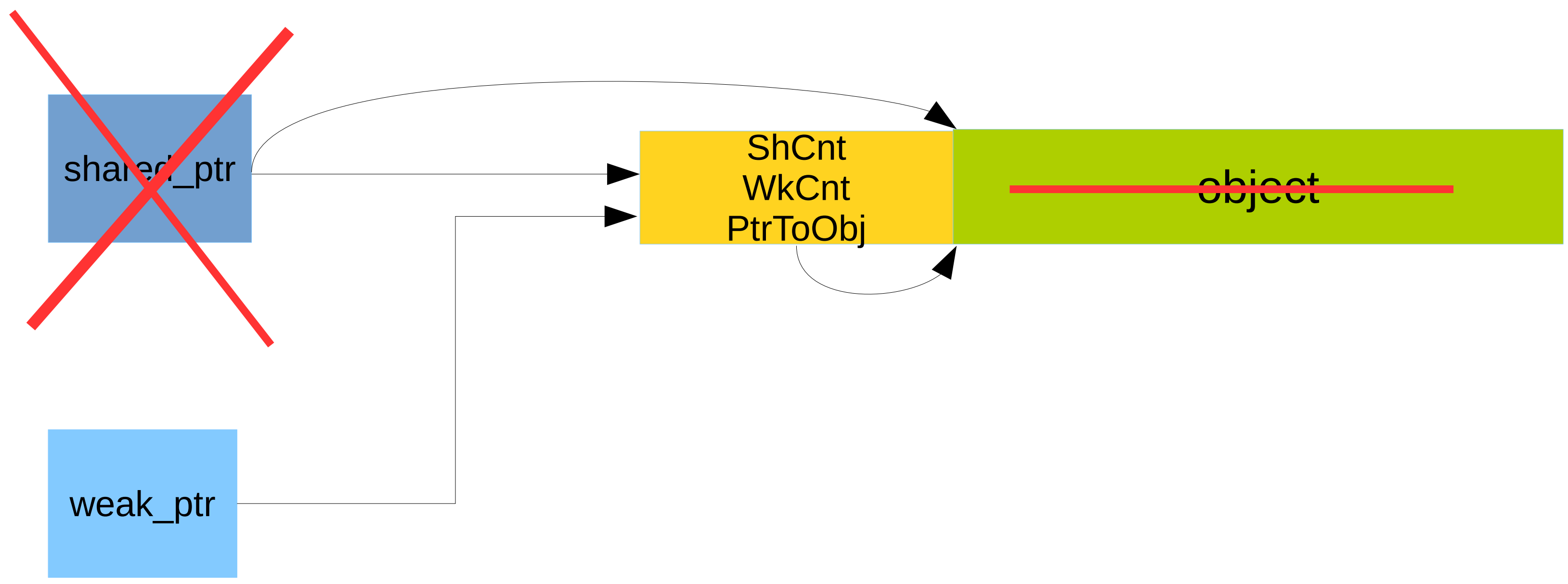
Trap: overuse of memory



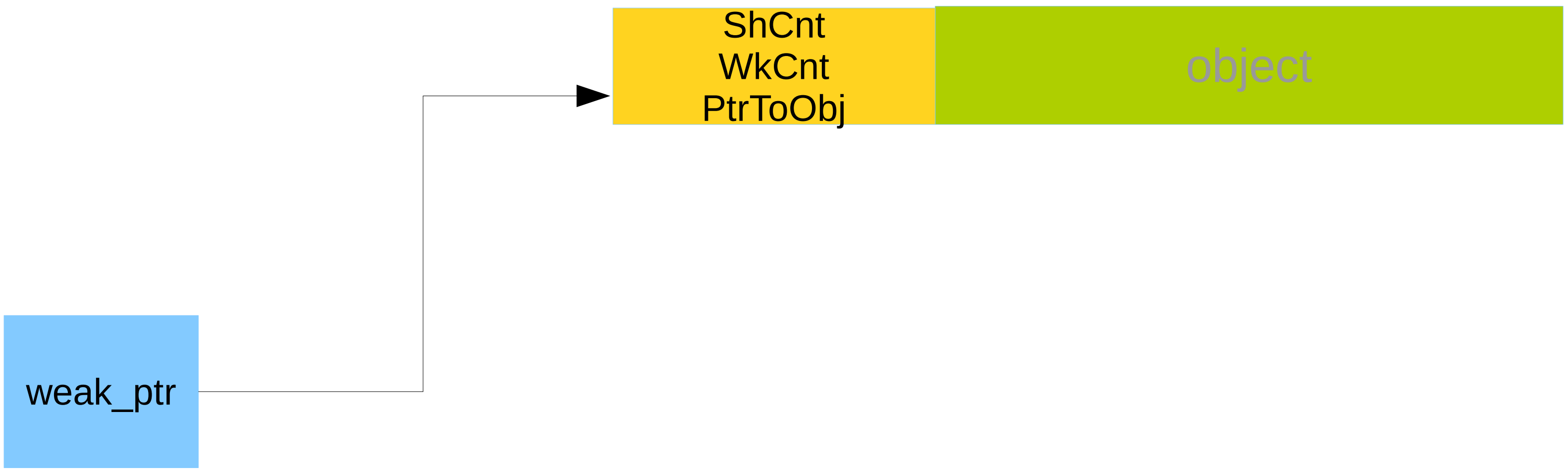
Trap: overuse of memory



Trap: overuse of memory



Trap: overuse of memory



When NOT to use make_*

- Both
  - You need custom deleter
  - You want to use braced initializer
- std::unique_ptr
  - You want custom allocator
- std::shared_ptr
  - Long living weak_ptrs
  - Class-specific new and delete
  - Potential false sharing of the object and the reference counter

Shared_ptr aliasing constructor

```
template< class Y >
shared_ptr( const shared_ptr<Y>& r, element_type* ptr ) noexcept;

// since C++20
template< class Y >
shared_ptr( shared_ptr<Y>&& r, element_type* ptr ) noexcept;
```

- Shares owneship with r
  - Reference counter is common with r
- Points to p
  - get() and - > returns p

Shared_ptr aliasing constructor

```
struct Data {
  int _i;
  Data( int i) : _i{i} { }
  virtual ~Data()  { std::cout<<"Data::~Data(): "<<_i<<"\n"; }
};
struct Wrapper {
  Data _data;
  Wrapper(int i) : _data{i} { }
  ~Wrapper()  { std::cout<<"Wrapper::~Wrapper(): "<<_data._i<<"\n"; }
};
int main()
{
  {
    Wrapper{1};
    const Data &dr = Wrapper{2}._data;
    std::cout << "end block\n";
  }
}
```

Shared_ptr aliasing constructor

```
struct Data {
  int _i;
  Data( int i) : _i{i} { }
  virtual ~Data()  { std::cout<<"Data::~Data(): "<<_i<<"\n"; }
};
struct Wrapper {
  Data _data;
  Wrapper(int i) : _data{i} { }
  ~Wrapper()  { std::cout<<"Wrapper::~Wrapper(): "<<_data._i<<"\n"; }
};
int main()
{
  {
    Wrapper{1};
    const Data &dr = Wrapper{2}._data;  // lifetime extension
    std::cout << "end block\n";
  }
}
```

```
Wrapper::~Wrapper(): 1
Data::~Data(): 1
end block
Wrapper::~Wrapper(): 2
Data::~Data(): 2
```

Shared_ptr aliasing constructor

```
struct Data {
  int _i;
  Data( int i) : _i{i} { }
  virtual ~Data()  { std::cout<<"Data::~Data(): "<<_i<<"\n"; }
};
struct Wrapper {
  Data _data;
  Wrapper(int i) : _data{i} { }
  ~Wrapper()  { std::cout<<"Wrapper::~Wrapper(): "<<_data._i<<"\n"; }
};
int main()
{
  {
    std::shared_ptr<Wrapper> wp = std::make_shared<Wrapper>(1);
    std::shared_ptr<Data>    dp(wp, &wp->_data);
    wp.reset();
    std::cout << dp->_i << '\n';
    std::cout << "end block\n";
  }
}
```

```
1
end block
Wrapper::~Wrapper(): 1
Data::~Data(): 1
```

for_overwrite (C++20)

```
auto ap1 = std::make_unique<int[]>(1000); // creates 1000 int

for ( auto i = 0; i < 1000; ++i)
    ap1[i] = i;   // overwrites the elements
```

for_overwrite (C++20)

```
auto ap1 = std::make_unique<int[]>(1000); // creates 1000 int
                                         // and initialize each to 0
for ( auto i = 0; i < 1000; ++i)
    ap1[i] = i;   // overwrites the elements
```

for_overwrite (C++20)

```
auto ap1 = std::make_unique<int[]>(1000); // creates 1000 int
                                         // and initialize each to 0
for ( auto i = 0; i < 1000; ++i)
    ap1[i] = i;   // overwrites the elements


auto ap2 = std::make_unique_for_overwrite<int[]>(1000); // creates 1000 int
                                         // elements are not initialized
for ( auto i = 0; i < 1000; ++i)
    ap2[i] = i;   // overwrites the elements

// similarly for shared_ptr
auto ap3 = std::make_shared_for_overwrite<int[]>(1000); // creates 1000 int
                                         // elements are not initialized
```

for_overwrite (C++20)

```
auto ap1 = std::make_unique<int[]>(1000); // creates 1000 int
                                         // and initialize each to 0
for ( auto i = 0; i < 1000; ++i)
    ap1[i] = i;   // overwrites the elements


auto ap2 = std::make_unique_for_overwrite<int[]>(1000); // creates 1000 int
                                         // elements are not initialized
for ( auto i = 0; i < 1000; ++i)
    ap2[i] = i;   // overwrites the elements

// similarly for shared_ptr
auto ap3 = std::make_shared_for_overwrite<int[]>(1000); // creates 1000 int
                                         // elements are not initialized


auto ap4 = std::make_unique_for_overwrite<int[]>(1000); // creates 1000 int
++ap[4];   // undefied behavior
```