Generic Pointers

Generic Data Structures

Stacks

- We defined stacks of strings
- But,
  - the code for stacks of ints would be identical except for string changed to int
  - the code for stacks of *any type* would be identical except for string changed to this type
  - …

```
/************ Implementation ***********/

typedef struct list_node list;
struct list_node {
  string data;
  list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

// typedef ______* stack_t;

bool stack_empty(stack_t S)
/*@requires S != NULL; @*/ ;

stack_t stack_new()
/*@ensures \result != NULL; @*/
/*@ensures stack_empty(\result); @*/ ;

void push(stack_t S, string x)
/*@requires S != NULL; @*/
/*@ensures !stack_empty(S); @*/ ;

string pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

Stacks

- Each time we need a stack for a new element type, we need to make a **copy** of the stack library
- This is **bad**
  - It's easy to make a mistake
  - We need to come up with new names
    - int_stack_t, int_stack_empty, …
    - int_list, int_list_node, is_int_segment, …
  - If we discover a bug, we need to fix it in **every copy** of the library
    - same if we discover a better implementation
- For a large application, this quickly becomes unmanageable

```
/************ Implementation ***********/

typedef struct list_node list;
struct list_node {
  string data;
  list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

// typedef ______* stack_t;

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void push(stack_t S, string x)
/*@requires S != NULL; @*/
/*@ensures !stack_empty(S); @*/ ;

string pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

Generic Data Structures

- Stacks are intrinsecally **generic data structures**
  - They work the same way no matter the type of their elements
  - They do not modify elements
    - they only store them in the data structure and give them back

- We would like to implement them as a **generic library**
  - a **single** stack implementation that can be used for elements of any type
    - without copying it over and over
    - without a proliferation of function and type names
  - if we find a bug, there is **one place** where to fix it
    - if we are told of a better implementation, there is **one file** to change

Generic Stacks -- Take 1

- Here's an idea:
  - use a generic type name elem in the library
  - let the client define what elem is
- We note the type elem is to be defined by the client in the **client interface**
- The client needs to define what elem actually is in the **client definition code**

```
/******** Client definitions ********/

typedef string elem;
```

```
/*********** Client Interface ***********/
// typedef ______ elem;

/*********** Implementation ***********/
typedef struct list_node list;
struct list_node {
  elem data;
  list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

// typedef ______* stack_t;

bool stack_empty(stack_t S)
/*@requires S != NULL; @*/ ;

stack_t stack_new()
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void push(stack_t S, elem x)
/*@requires S != NULL; @*/
/*@ensures !stack_empty(S); @*/ ;

elem pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

Generic Stacks -- Take 1

Pros:

- A **single** library for any kind of stack
  - If the client needs a stack of ints in a different application,
    - simply define elem as int
  - If another application requires a different stack type, just define elem appropriately

```
/******** Client definitions ********/

typedef int elem;
```

```
/*********** Client Interface ***********/
// typedef ______ elem;

/*********** Implementation ***********/
typedef struct list_node list;
struct list_node {
 elem data;
 list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

// typedef ______* stack_t;

bool stack_empty(stack_t S)
/*@requires S != NULL; @*/ ;

stack_t stack_new()
/*@ensures \result != NULL; @*/
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void push(stack_t S, elem x)
/*@requires S != NULL; @*/
/*@ensures !stack_empty(S); @*/ ;

elem pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

Generic Stacks -- Take 1

Cons:

- Client application has to be split into **two** files
  - ➢ Client definition file

```
/***** Client definitions *****/

typedef string elem;
```

  - ➢ Rest of the client application

```
/* Client application */

int main() {
   … push … pop …
}
```

This is mildly annoying

- ○ because
  - ➢ the library needs elem to be defined
    - ❑ This must occur **before** the library
  - ➢ the client application needs the types and functions provided by the library to be defined
    - ❑ This must occur **after** the library

```
/*********** Client Interface ***********/
// typedef ______ elem;

/*********** Implementation ***********/
typedef struct list_node list;
struct list_node {
  elem data;
  list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

// typedef ______* stack_t;

bool stack_empty(stack_t S)
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/*@requires S != NULL; @*/
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elem pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```
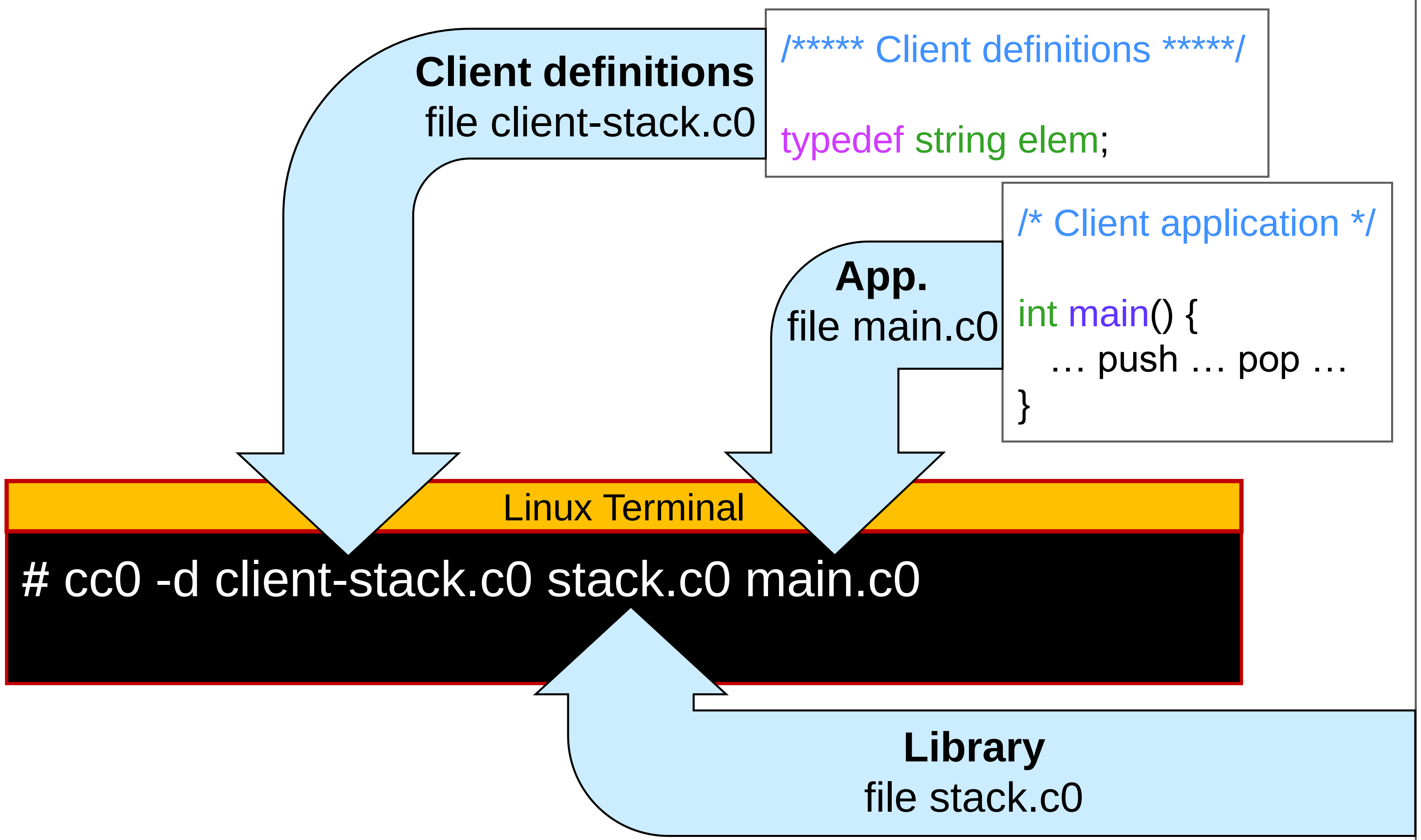

Generic Stacks -- Take 1




```
/************ Client Interface ***********/
// typedef ______ elem;

/************ Implementation ***********/
typedef struct list_node list;
struct list_node {
  elem data;
  list* next;
};

typedef struct stack_header stack;
…

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elem pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

- This forces an **unnatural compilation pattern**

> This is mildly annoying

Generic Stacks -- Take 1

Cons:

- Client application can contain at most **one type** of stacks
  - no way to have both a stack of strings and a stack of ints in the **same** application
    - but we can have multiple stacks of ints
  - because there can be only **one definition** for elem

This is a big deal

```
/***** Client definitions *****/

typedef string elem;
typedef int    elem;
```

?

The compiler won't know which elem to use when

Compilation error!

```
/************ Client Interface ***********/
// typedef ______ elem;

/************ Implementation ***********/
typedef struct list_node list;
struct list_node {
  elem data;
  list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

// typedef ______* stack_t;

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void push(stack_t S, elem x)
/*@requires S != NULL; @*/
/*@ensures !stack_empty(S); @*/ ;

elem pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

Generic Stacks -- Take 1

Summary

- **Pros:**
  - A single library for any kind of stacks
- **Cons:**
  - Client application is split into **two** files
    - Unnatural compilation pattern
  - Client application can contain at most **one type** of stacks

This is mildly annoying

This is a big deal

```
/************ Client Interface ***********/
// typedef ______ elem;

/************ Implementation ***********/
typedef struct list_node list;
struct list_node {
  elem data;
  list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

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/*@requires S != NULL; @*/
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elem pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

Can we do Better?

- Not in C0 …

- … but the language C1 extends C0 with a mechanism to address these issues

C1

The language C1

- C1 is an **extension** of C0
  - Every C0 program is a C1 program

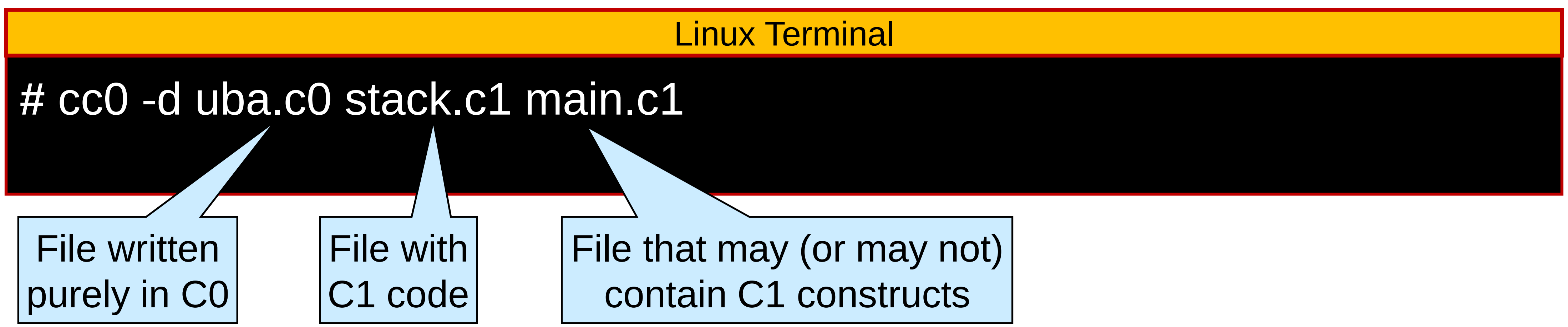
- C1 provides two additional mechanisms
  - Generic pointers
  - Function pointers

  Both help with genericity

- Right now, we will only examine generic pointers

Running C1 Programs

- C1 programs are compiled with cc0
  - but C1-only constructs are only allowed in files with a **.c1** extension
    - C0-only code can appear in files with either a .c0 or a .c1 extension
- Example



- The coin interpreter does not currently support C1 constructs
  - no way to experiment with them in coin

Generic Pointers

void*

This is **not** a pointer to void:
void is not a type
Blame C for the confusing name!

- C1 provides a new **pointer type**: void*

```
void* q;
```

q is a variable of type void*

  - a value of this type is a **generic pointer**

- Any pointer can be turned into a void* using a **cast**

```
int* p = alloc(int);
*p = 7;
q = (void*)p;
```

Cast p to void*

q still has type void*,
but contains the same address of p

  - and later back to its original type

```
int* r = (int*)q;
```

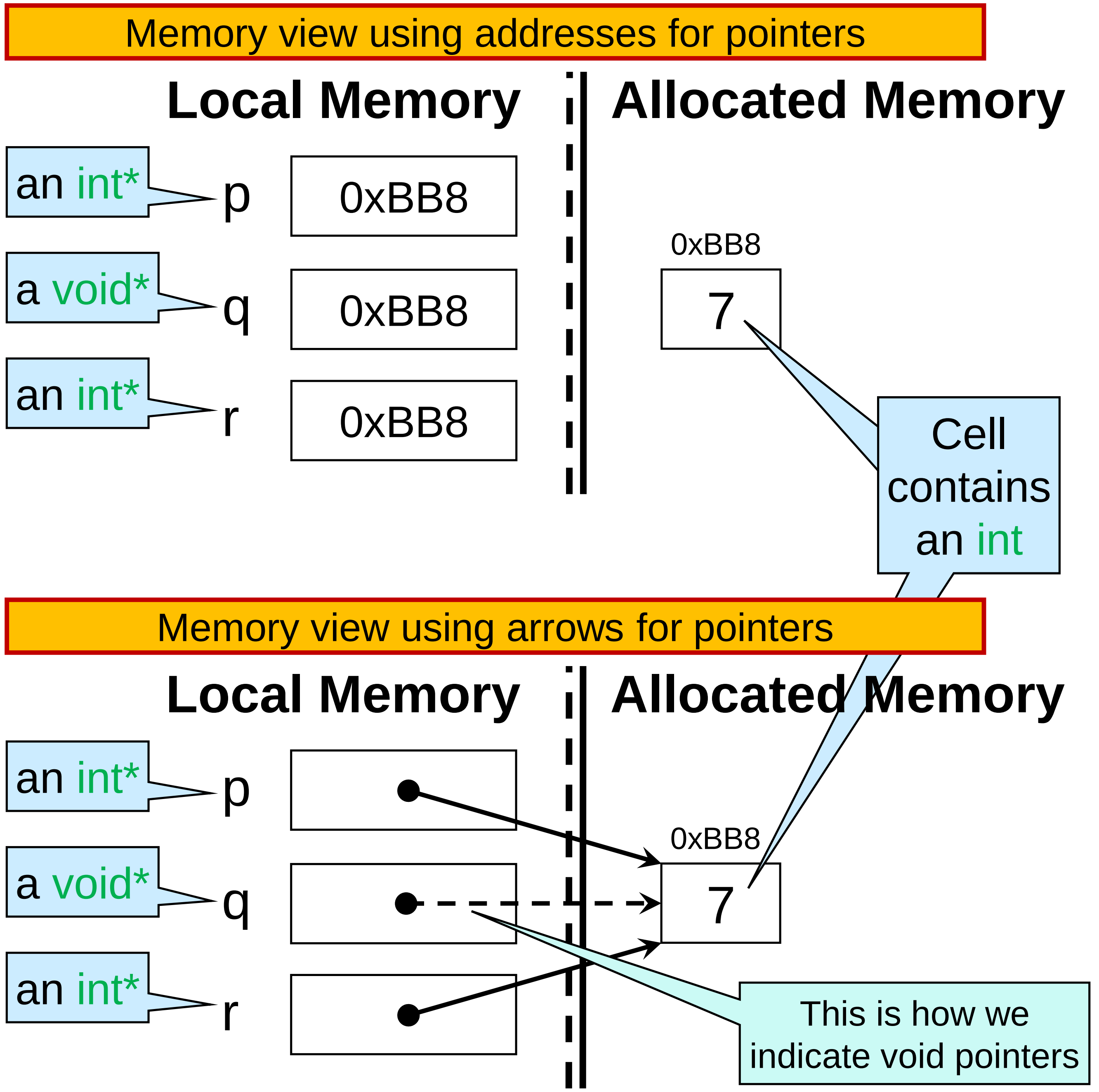
Cast q to int*

q still has type void*,
but r contains the same address as p

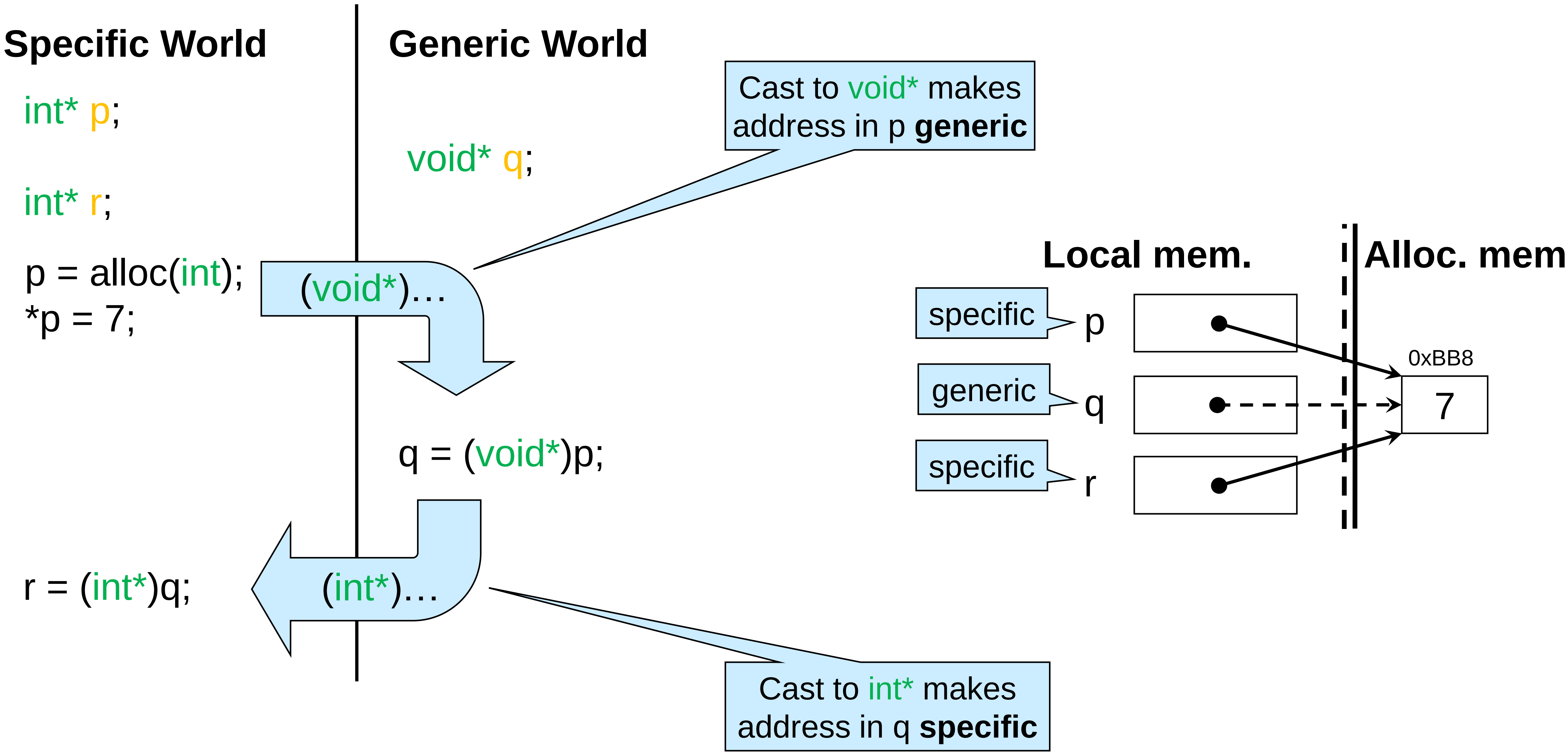
void*

```
void* q;
int* p = alloc(int);
*p = 7;
q = (void*)p;
int* r = (int*)q;
```

- p, q and r contain the same address
  - they are aliases
- but
  - p and r have type int*
  - q has type void*
- With casting, we can pretend that a **specific** pointer (e.g., an int*) is a **generic** pointer (void*)
  - a controlled way for a pointer to have two types
  - *only for pointers*



The Specific/Generic Divide



What can we do with void* Pointers?

Allowed

- Cast to original type

```
int* p = alloc(int);
void* q1 = (void*)p;
int* r = (int*)q1;      ✓
```

- Compare for equality

```
void* q2 = (void*)alloc(int);
if (q1 == q2) println("same");   ✓
```

- Assign to a void* variable
  - void* q3 = q1;   ✓

Not Allowed

- Dereference

```
void x = *q1;   ✗
```

  - void is **not** a type in C0/C1/C

- Allocate

```
void* q4 = alloc(void);   ✗
```

  - void is not a type

- Cast to type other than original

```
println((string*)q1);   ✗
```

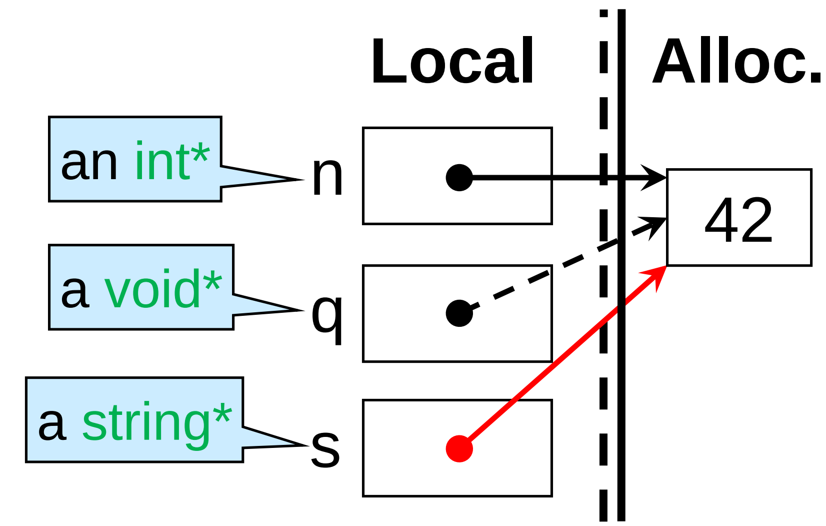
  - *(see next)*

Safety of Generic Pointers

Casting back to the Wrong Type

```
int main() {

  int* n = alloc(int);
  *n = 42;

  void* q = (void*)n;

  string* s = (string*)q;

  print(*s);

  return 0;
}
```

- n is an int*
- q is a void* that secretly points to an int*
- this turns an int* into a string* ??
- What ????



- This makes no sense!!!
  - dereferencing s, we get to an int (42)
  - but print expects a string

  This doesn't feel right
    - a safety violation maybe?

Casting back to the Wrong Type

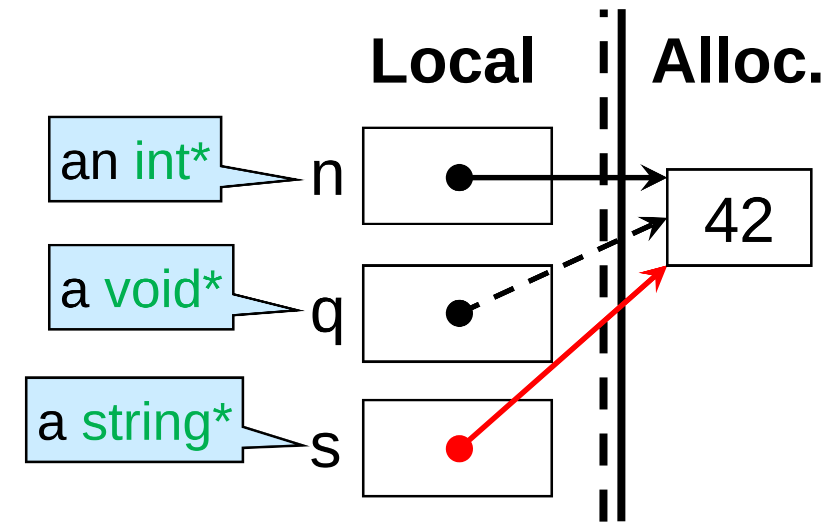
```
int main() {

  int* n = alloc(int);
  *n = 42;

  void* q = (void*)n;

  string* s = (string*)q;

  print(*s);

  return 0;
}
```

n is an int*

q is a void* that secretly points to an int*

this turns an int* into a string* ??

What ????



- Let's run it

Linux Terminal

```
# cc0 -d bad-casting.c1
# ./a.out
untagging pointer failed
Segmentation fault (core dumped)
```

- We get a memory error
- This **is** a safety violation

Tags

```
int main() {

  int* n = alloc(int);
  *n = 42;

  void* q = (void*)n;

  string* s = (string*)q;

  print(*s);

  return 0;
}
```

n is an int*

q is a void* that secretly point

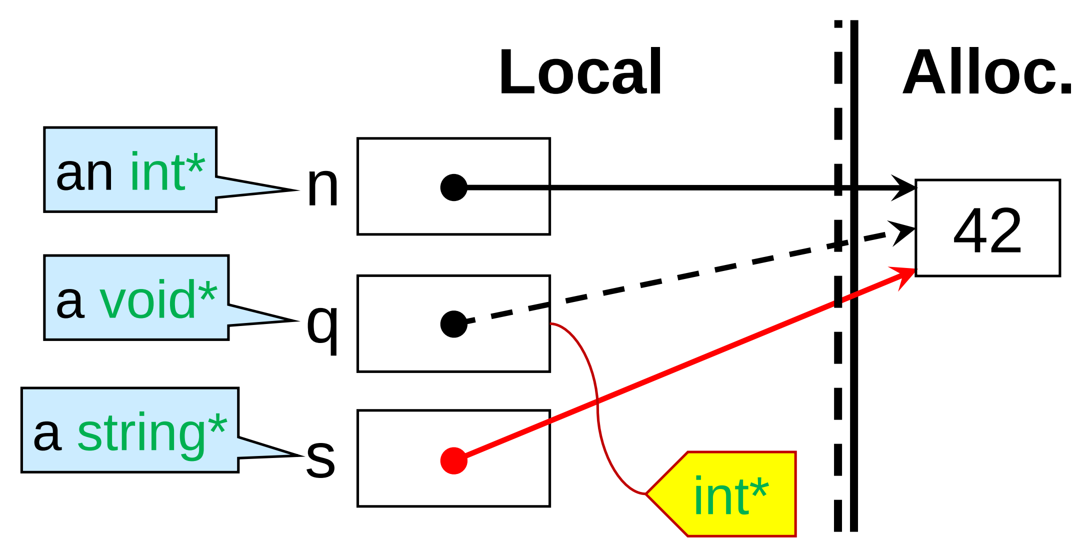
this turns an int* into a string*

What ????

Linux Terminal

```
# cc0 -d bad-casting.c1
# ./a.out
untagging pointer failed
Segmentation fault (core dumped)
```

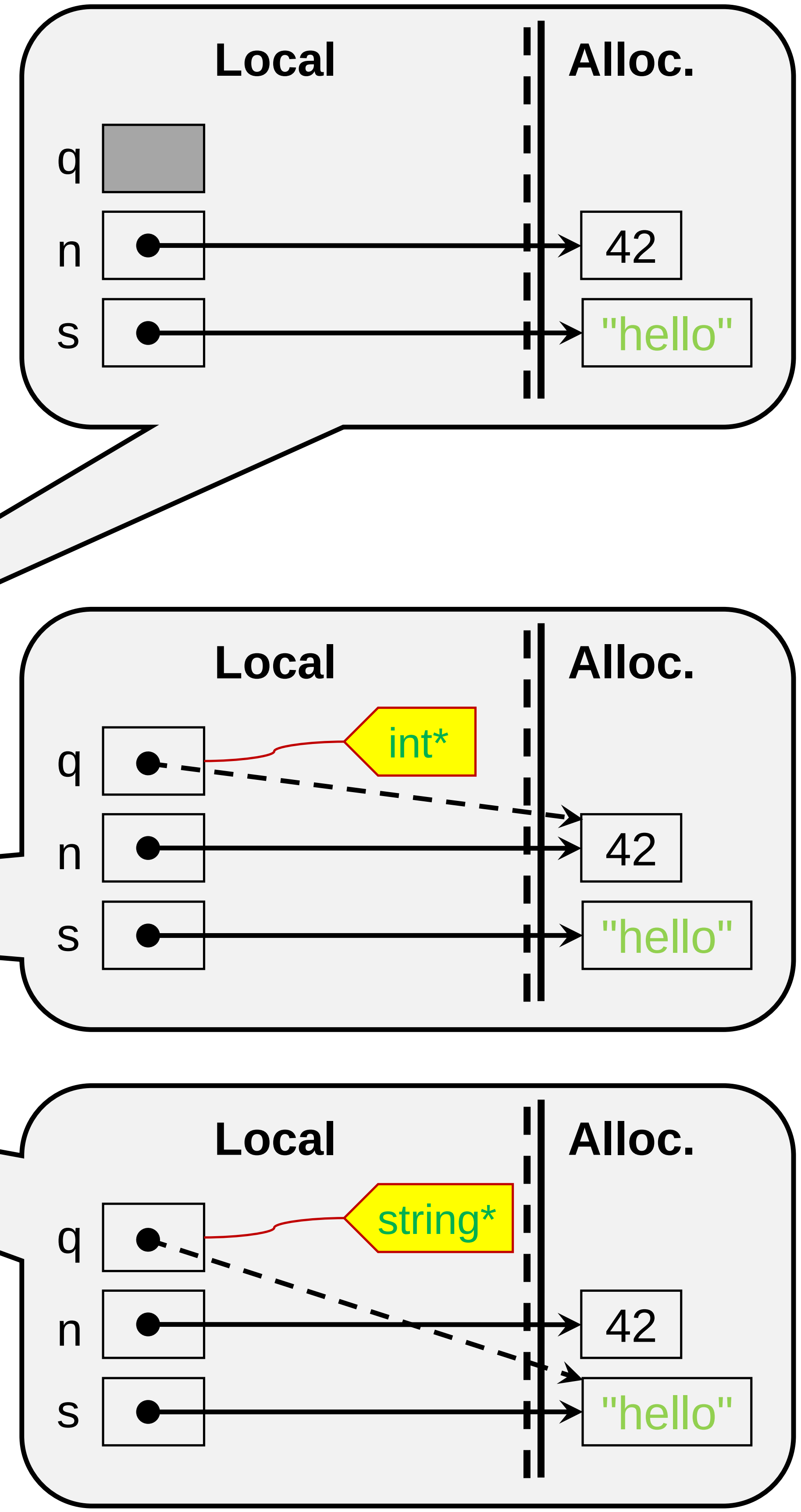
- *Untagging pointer failed?*
  - At run time, values of type void* carry a **tag** that records the original type of the pointer
  - C1 checks that the tag is correct before casting back



Tags

- The tag of a void* changes as execution proceeds

```
int main() {
  void* q;

  int* n = alloc(int);
  *n = 42;

  string* s = alloc(string);
  *s = "hello";

  q = (void*)n;
  printint(*(int*)q);

  q = (void*)s;
  print(*(string*)q);

  return 0;
}
```

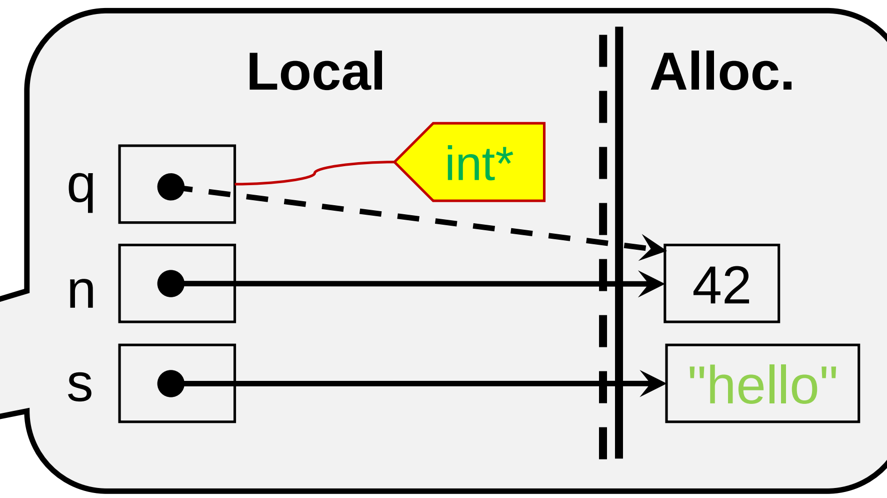


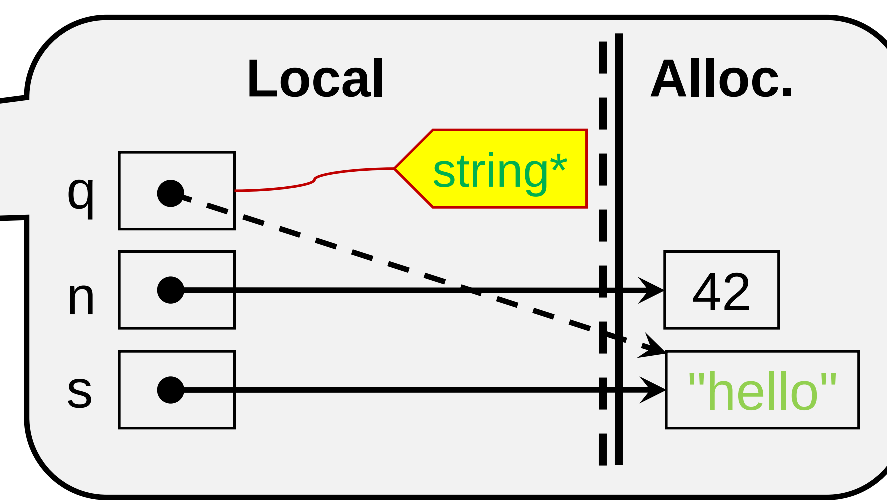
\hastag

- Annotation-only function \hastag(tp, ptr) can be used to check that generic pointer ptr has type tp *in debugging mode*

```
int main() {
  void* q;

  int* n = alloc(int);
  *n = 42;

  string* s = alloc(string);
  *s = "hello";

  q = (void*)n;
  //@assert \hastag(int*, q);
  printint(*(int*)q);

  q = (void*)s;
  //@assert \hastag(string*, q);
  //@assert !\hastag(int*, q);
  print(*(string*)q);

  return 0;
}
```

Checks that q has tag int*





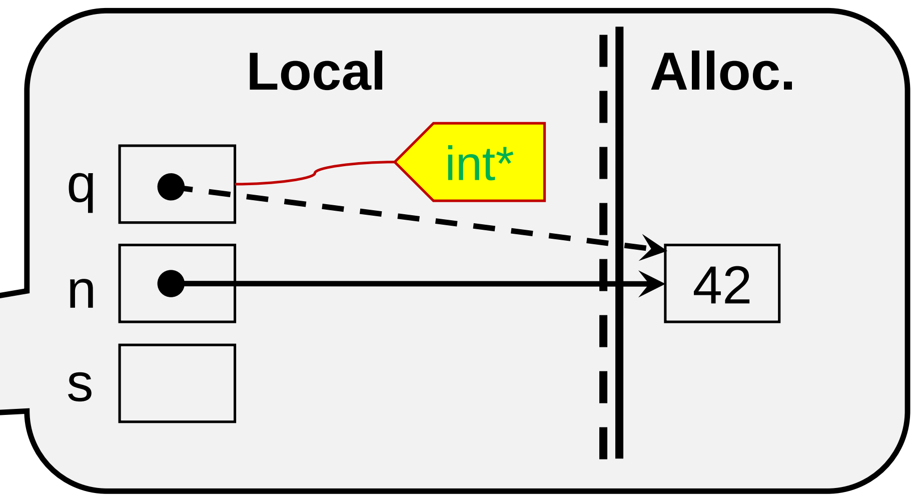
Checks that q now has tag string*

Checks that q does not have tag int*

\hastag

- *Annotation-only function \hastag(tp, ptr) can be used to check that generic pointer ptr has type tp in debugging mode*

```
int main() {

  int* n = alloc(int);
  *n = 42;

  void* q = (void*)n;
  //@assert \hastag(int*, q);

   //@assert \hastag(string*, q);
  string* s = (string*)q;

  print(*s);

  return 0;
}
```



Checks that q has tag int*

Checks that q has tag string*

- Use \hastag before casting a void* back to a specific type

NULL

- NULL is a pointer of any type, including void*
  - We can cast NULL back and forth as we please

```
int* p = NULL;
void* q = (void*)p;
string* r = (string*)q;
```

This is legal because q is NULL

  - or do even wilder things

```
void* q = NULL;
void* r = (void*)(int*)(void*)(string*)q;
```

This is legal because q is NULL

- A NULL variable of type void* has *every* tag

```
void* v = NULL;
//@assert \hastag(int*, v);
//@assert \hastag(string*, v);
```

This is legal because v is NULL

  - except void*

```
//@assert \hastag(void*, v);
```

This causes a compilation error

Contracts of Cast Operations

- Casts are **potentially unsafe** operations over pointer expressions
  - With \hastag, we can write contracts for them

- Casting from specific to generic type
  - (void*)x where x was declared of type tp*

```
(void*)x
//@ensures \hastag(tp*, \result);
```

- Casting from generic to specific type
  - (tp*)q where q was declared of type void*

```
(tp*)q
//@requires \hastag(tp*, q);
```

Generic Stacks in C1

Generic Stacks

Use void* as the type of the elements

- **Pros:**
  - Simple change to the library

    typedef void* elem;

    That's it!
  - A single library for any kind of stacks
- **Cons:**
  - Stack elements must be pointers
    - We cannot have a stack of ints
    - We need to turn them into int*
  - This is the best we will be able to do
    - genericity is limited to pointers
    - not just in C1, but also in C

```
/************ Implementation ***********/
typedef void* elem;      // Element type

typedef struct list_node list;
struct list_node {
  elem data;
  list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

// typedef ______* stack_t;

bool stack_empty(stack_t S)
/*@requires S != NULL; @*/ ;

stack_t stack_new()
/*@ensures \result != NULL; @*/
/*@ensures stack_empty(\result); @*/ ;

void push(stack_t S, elem x)
/*@requires S != NULL; @*/
/*@ensures !stack_empty(S); @*/ ;

elem pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

Converting an int* Stack to Generic

- Cast elements to void* when pushing
- Cast them back to int* when popping

main.c0

```
int main() {
  stack_t l = stack_new();

  int* x = alloc(int);
  *x = 42;
  push(l, x);

  int* y = alloc(int);
  *y = 15122;
  push(l, y);

  int* z = pop(l);
  printint(*z); println("");

  printint(*pop(l));

 return 0;
}
```

push now expects a void* ;
cast x to a temp variable of type void*

Same thing, done inline

pop returns a void*, but z has type int*

Same thing, inline

main.c1

```
int main() {
  stack_t l = stack_new();

  int* x = alloc(int);
  *x = 42;
  void* p = (void*)x;
  push(l, p);

  int* y = alloc(int);
  *y = 15122;
  push(l, (void*)y);

  int* z = (int*)pop(l);
  printint(*z); println("");

printint(*(int*)pop(l));

 return 0;
}
```

Compilation

```
int main() {
  stack_t l = stack_new();

  int* x = alloc(int);
  *x = 42;
  void* p = (void*)x;
  push(l, p);

  int* y = alloc(int);
  *y = 15122;
  push(l, (void*)y);


  int* z = (int*)pop(l);
  printint(*z); println("");

printint(*(int*)pop(l));

 return 0;
}
```

```
/************ Implementation ***********/
typedef void* elem;      // Element type

typedef struct list_node list;
struct list_node {
  elem data;
  list* next;
};

typedef struct stack_header stack;
…

/*************** Interface ***************/

// typedef ______* stack_t;

bool stack_empty(stack_t S)
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stack_t stack_new()
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void push(stack_t S, elem x)
/*@requires S != NULL; @*/
/*@ensures !stack_empty(S); @*/ ;

elem pop(stack_t S)
/*@requires S != NULL; @*/
/*@requires !stack_empty(S); @*/ ;
```

Application
file main.c1

Linux [illegible]inal

```
# cc0 -d stack.c1 main.c1
```

Library
file stack.c1

No need for a client-stack.c1 file!

Converting an int Stack to Generic

- No way to store an int into a generic stack
  - We need to convert elements to int* first
    - And cast them to void* to use the stack

This is annoying
… but that's the best we can do

main.c0

```
int main() {
  stack_t l = stack_new();



  push(l, 42);


  int y = 15122;
  push(l, y);

  int z = pop(l);
  printint(z); println("");

  printint(pop(l));

 return 0;
}
```

main.c1

```
int main() {
  stack_t l = stack_new();

  int* x = alloc(int);
  *x = 42;
  void* p = (void*)x;
  push(l, p);

  int* y = alloc(int);
  *y = 15122;
  push(l, (void*)y);

  int z = *(int*)pop(l);
  printint(*z); println("");

printint(*(int*)pop(l));

 return 0;
}
```

- We must store 42 in allocated memory, and cast its pointer to a temp variable of type void*
- We can inline the cast, but not the allocation
- pop returns a void*, but z has type int*
- Same thing, inline

Using two Stacks of Different Type in C0

… in the same application

- We need to have two copies of the stack library
  - *int_stack* for ints and *str_stack* for strings

main.c0

```
int main() {
  int_stack_t I = int_stack_new();    // a stack of ints
  int_push(I, 42);
  int y = 15122;
  int_push(I, y);
  int z = int_pop(I);
  printint(z); println("");
  printint(int_pop(I));

  str_stack_t S = str_stack_new();  // a stack of strings
  str_push(S, "hello");
  string s = "world";
  str_push(S, s);
  string w = str_pop(S);
  println(w);
  println(str_pop(S));

 return 0;
}
```

Using two Stacks of Different Type in **C1**

… in the same application

- The one generic stack library is enough
- but we need to convert elements to be pointers

main.c1

```
int main() {
 stack_t I = stack_new();   // a stack for ints

  int* x = alloc(int);
  *x = 42;
  void* p = (void*)x;
  push(I, p);

  int* y = alloc(int);
  *y = 15122;
  push(I, (void*)y);

  int z = *(int*)pop(I);
  printint(z); println("");

  printint(*(int*)pop(I));

   // continued to the right
```

```
  // continued from left

  stack_t S = stack_new();  // a stack for strings

  string* s1 = alloc(string);
  *s1 = "hello";
  push(S, (void*)s1);

  string* s = alloc(string);
  *s = "world";
  push(S, (void*)s);

  string w = *(string*) pop(S);
  println(w);
  println(*(string*)(pop(S)));

 return 0;
}
```

Bad Uses of Generic Stacks

- Nothing prevents pushing elements of *different* type in the same generic stack
  - *but why would you want to do that???*

main.c1

```
int main() {
  stack_t X = stack_new();     // one stack

  int* i = alloc(int);
  *i = 42;
   push(X, (void*)i);       // push an int onto X

   string* s = alloc(string);
   *s = "Ouch!";
   push(X, (void*)s);      // now push a string onto X!

   string w = *(string*)pop(X);
   println(w);               // pop the string and print it

  printint(*(int*)pop(I)); // pop the int and print it

  return 0;
}
```

- Extremely error-prone

In general, how do we remember this element will be a string?

… and this one an int?

- There is always a cleaner way to do this