Systems and Internet Infrastructure Security

Network and Security Research Center
Department of Computer Science and Engineering
Pennsylvania State University, University Park PA

CMPSC 447
Type Errors

Trent Jaeger
Systems and Internet Infrastructure Security (SIIS) Lab
Computer Science and Engineering Department
Pennsylvania State University

Type Errors

- Errors that permit access to memory according to a multiple, incompatible formats
    - These are called type errors
    - Access outside the expected "type"
- Most of these errors are permitted by simple programming flaws
    - Of the sort that you are not taught to avoid
    - Let's see how such errors can be avoided
- Some of the changes are rather simple

Temporal Errors

- A few of the exploits that we have discussed are the result of temporal errors

Type Confusion

- Many effective attacks exploit data of another type

```
struct A {
    struct C *c;
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

Type Confusion

- Adversary can abuse ambiguity to control writes

```
struct A {
    struct C *c;
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

```
x = (struct A *)malloc(sizeof(struct A));
y = (struct B *)x;
y->B1 = adversary-controlled-value;
x->c->field = adversary-controlled-value-also;
```

Type Confusion

PENNSTATE 1855

- Adversary can abuse ambiguity to control writes

```
struct A {
    struct C *c;
    char buffer[40];
};

struct B {
    int B1;
    int B2;
    char info[32];
};
```

```
x = (struct A *)malloc(sizeof(struct A));
y = (struct B *)x;
y->B1 = adversary-controlled-value;
x->c->field = adversary-controlled-value-also;
```

- Arbitrary Write Primitive!
    - Adversary controls the value to write and the location of the write
    - Allow adversary to write an arbitrary value to an arbitrary location

What Is Going Wrong?

- We have objects (memory regions) and references (pointers)
  - What goes wrong in type errors?

How Do Type Casts Work?

- We have objects (memory regions) and references (pointers)
  - What goes wrong in temporal errors?
- A pointer may reference a memory region using two different types (i.e., memory formats)
- Normal lifecycle between a pointer and object
  - t1 *p, t2 *q; // declare pointers
  - p = (t1 *) malloc(sizeof(t1)); // allocate object and define p
  - p→field = value; // use pointer for t1
  - q = (t2 *)p; // type cast and define q
  - q→X = value2; // use pointer for t2

How Do Type Casts Work?

- We have objects (memory regions) and references (pointers)
  - What goes wrong in temporal errors?
- A pointer may reference a memory region using two different types (i.e., memory formats)
- Normal lifecycle between a pointer and object
  - t1 *p, t2 *q; // declare pointers
  - p = (t1 *) malloc(sizeof(t1)); // allocate object and define p
  - p→field = value; // use pointer for t1
  - q = (t2 *)p; // type cast and define q
  - q→X = value2; // use pointer for t2

How Do Type Casts Work?

PENNSTATE 1855

- We have objects (memory regions) and references (pointers)
  - What goes wrong in temporal errors?
- A pointer may reference a memory region using two different types (i.e., memory formats)
- Normal lifecycle between a pointer and object
  - t1 *p, t2 *q; // declare pointers
  - p = (t1 *) malloc(sizeof(t1)); // allocate object and define p
  - p→field = value; // use pointer for t1
  - q = (t2 *)p; // type cast and define q
  - q→X = value2; // use pointer for t2

What Can Go Wrong?

PENNSTATE 1855

- A pointer may reference a memory region using two different types (i.e., memory formats)
- Normal lifecycle between a pointer and object
  - t1 *p, t2 *q; // declare pointers
  - p = (t1 *) malloc(sizeof(t1)); // allocate object and define p
  - p→field = value; // use pointer for t1
  - q = (t2 *)p; // type cast and define q
  - q→X = value2; // use pointer for t2
- Semantics of "p→field" may be different than "q→X"
  - Even if these reference the same memory location

What Can Go Wrong?

- Downcasts – Cast to a larger type; causes overflow
  - t1 *p, t2 *q; // declare pointers
  - p = (t1 *) malloc(sizeof (t1)); // allocate t1 object, define p
  - p→field = value; // suppose this is an int field
  - q = (t2 *)p; // downcast, t2 is a larger type
  - q→extra= value2; // overflow memory of object
- E.g., t2 is a child type of t1
  - So, the size of type t2 is greater than the size of type t1
  - "extra" field is added to the type t1 to create type t2

What Can Go Wrong?

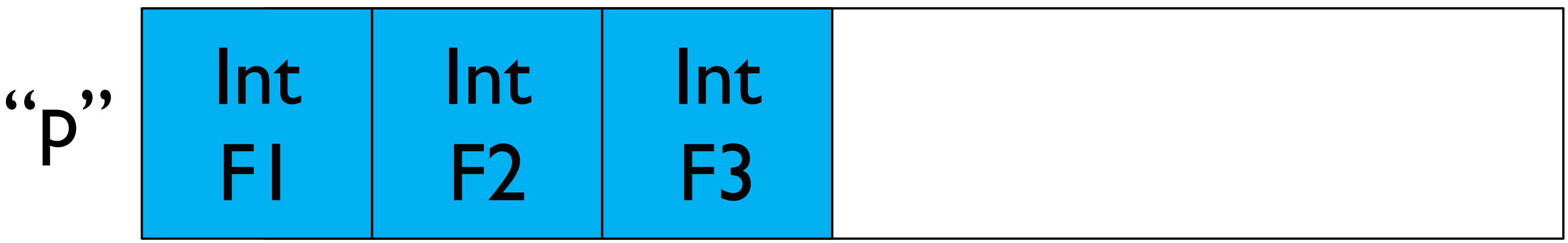
PENNSTATE

1855

- Downcasts – Cast to a larger type; causes overflow
  - t1 *p, t2 *q; // declare pointers
  - p = (t1 *) malloc(sizeof (t1)); // allocate t1 object, define p
  - p→field = value; // suppose this is an int field
  - q = (t2 *)p; // down cast, t2 is a larger type
  - q→extra = value2; // overflow memory of object
- By downcasting to the larger type t2 with the "extra" field, gives the adversary the ability to read/write beyond the memory region allocated
  - Memory region is the "sizeof(t1)" in size

Exploiting Type Errors

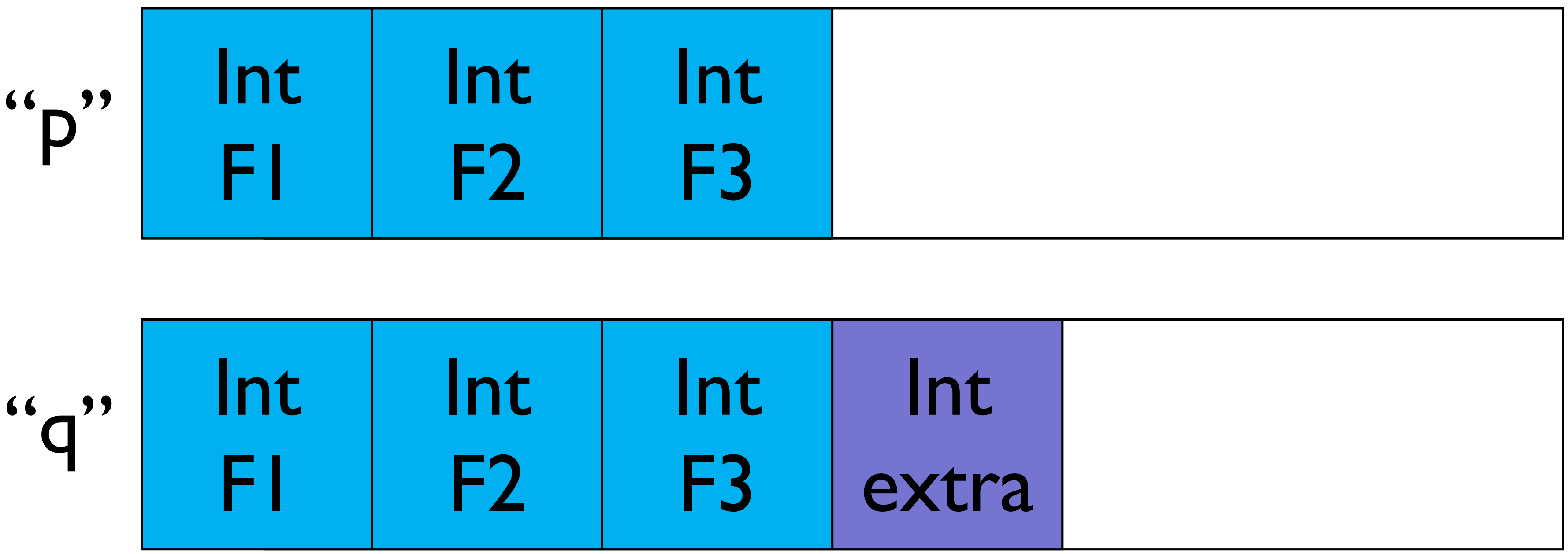
- Type t2 is a child type (downcast) of type t1



- Allocate object of type t1 and assign "p" to reference

Exploiting Type Errors

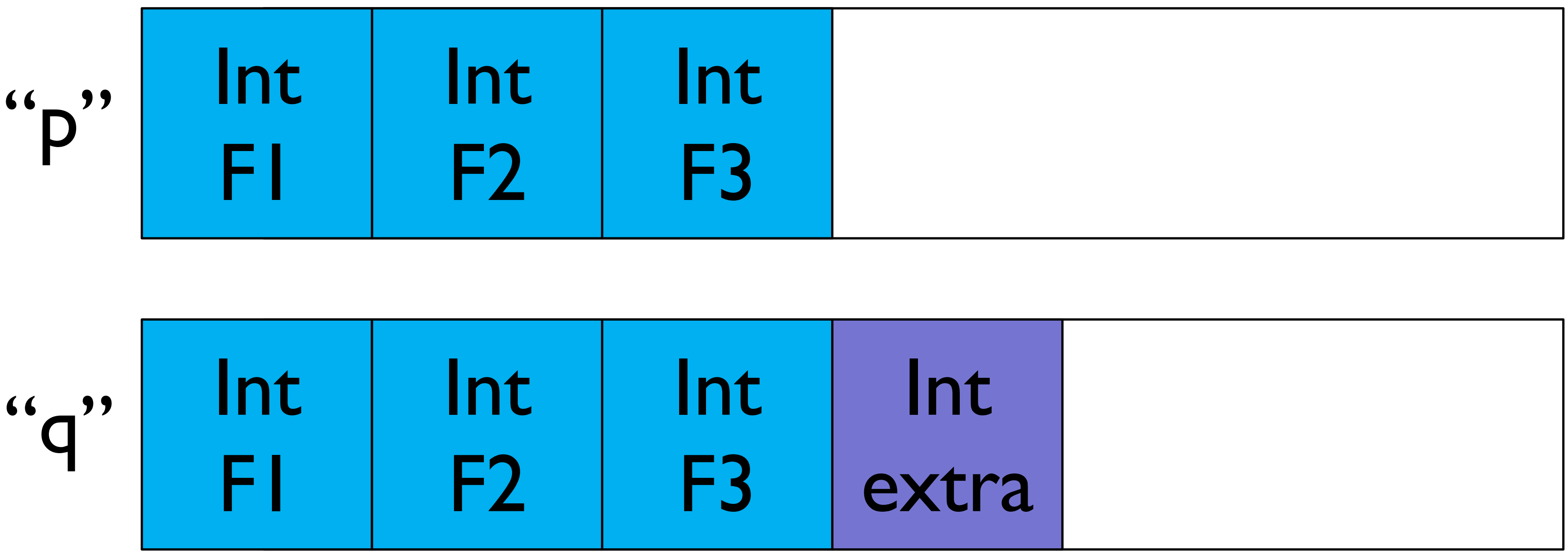
- Type t2 is a child type (downcast) of type t1



- Assign “q” of type t2 to the memory location of “p”
    - But, ”q” of type t2 thinks it is referencing a larger region

Exploiting Type Errors

- Type t2 is a child type (downcast) of type t1



- What will happen when the program accesses "q→extra"?

What Can Go Wrong?

- Type confusion – use data to craft a pointer
  - t1 *p, t2 *q; // declare pointers
  - p = (t1 *) malloc(sizeof(t1)); // allocate object and define p
  - p→field = value; // suppose "field" is an int field
  - q = (t2 *)p; // type cast and define q
  - q→X→target = value2; // suppose "X" is a pointer field
- "p→field" is a data field, so may store adversary data
- But, "q→X" is a pointer field
  - Should we allow adversaries to define pointer values?

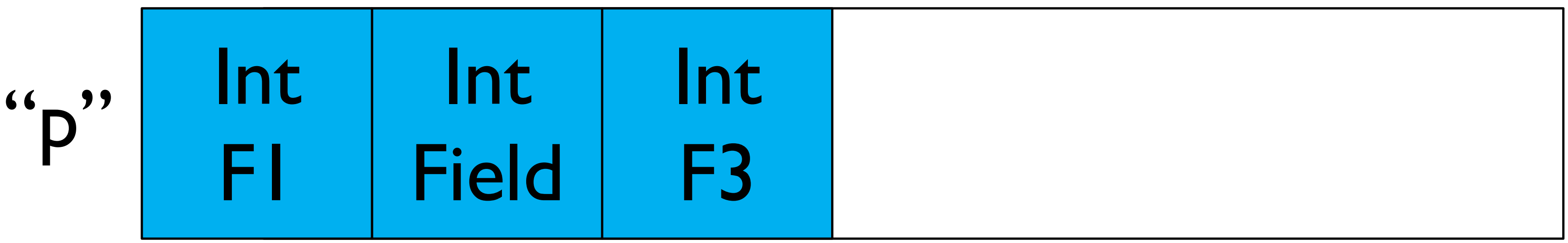
What Can Go Wrong?

PENNSTATE 1855

- Type confusion – use an integer to craft a pointer
  - t1 *p, t2 *q; // declare pointers
  - p = (t1 *) malloc(sizeof(t1)); // allocate object and define p
  - p→field = value; // suppose "field" is an int field
  - q = (t2 *)p; // type cast and define q
  - q→X→target = value2; // suppose "X" is a pointer field
- The write to "field" of type "p" gives the adversary the ability to choose a memory location for the write to "X" – if at the same offset as "field"
  - To modify an adversary-chosen memory location
  - Relative to the field "target"

Exploiting Type Errors

- Type t2 is unrelated to type t1



- Allocate object of type t1 and assign "p" to reference

Exploiting Type Errors

- Type t2 is unrelated to type t1

- The offset of "Field" from "p" of type t1 and "X" from "q" of type t2 are the same

Exploiting Type Errors

- Type t2 is unrelated to type t1

- Assign an adversary-controlled value at "p→Field"

Exploiting Type Errors

- Type t2 is unrelated to type t1

- But, program accesses "q→X" as a pointer
  - What can an adversary do?

Exploiting Type Errors

- Type t2 is unrelated to type t1

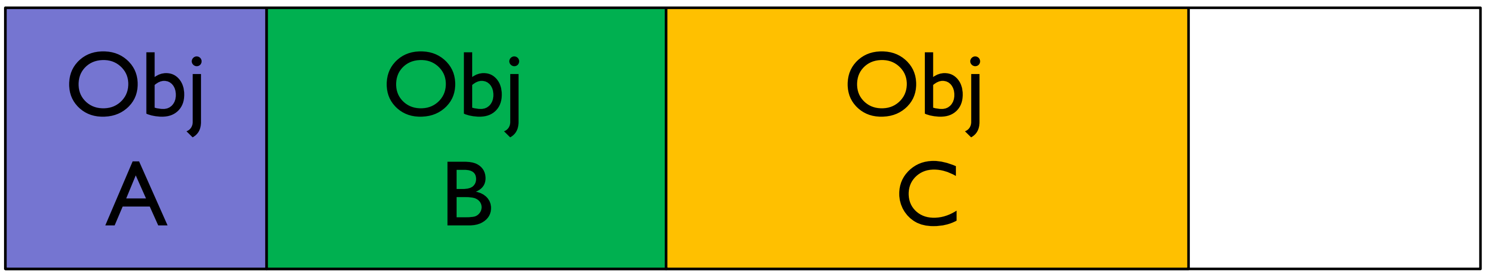
- But, program accesses “q→X” as a pointer
  - Adversary chose the address stored at ”q→X”
  - Thus, the adversary can choose the memory to access

Exploiting Type Errors

- Project 2
  - What object can be accessed by pointers of multiple types?
  - Is there a flaw that allows you to create an object of one type …
  - And access that object with a pointer of a different type?
  - Can you find a target that you can modify using the mismatched type's pointer?
  - What do you want to exploit if you can modify the target?
  - Craft the payload to cause a modification that implements the desired exploit

Exploiting Type+Temporal Errors

- With temporal errors



- Can also exploit type confusion using temporal errors, such as use-after-free
  - Obj B of type B is deallocated, but has a stale pointer “b”
  - Obj D of a different type D is allocated in that free slot
  - Then, a use-after-free flaw can use “b” of type B to access Obj D of a different type D

Integer Overflows

- Yet, another issue (probably the last one) to consider
  - NOTE: Very different from buffer overflows
- Key question
  - What is an integer?
  - In a computer system?

Integer Overflows

- Yet, another issue (probably the last one) to consider
  - NOTE: Very different from buffer overflows
- Key question
  - What is an integer?
  - In a computer system?
- There are several different computer representations for integers
  - Size – number of bytes used to represent
  - Signedness – range of values integers can take

Integer Overflows

- Suppose we have an 8-bit integer type
  - How many values can it represent?
  - What range of values can it represent?

Integer Overflows

PENNSTATE 1855

- Suppose we have an 8-bit, signed integer type
  - How many values can it represent?
    - $2^8 = 256$
  - What range of values can it represent?
    - Depends on whether it is "signed" or nott
  - What are the range of values if "unsigned"?
    - 0 to 255
  - What are the range of values if "signed"?
    - -128 to 127

Integer Overflows

- Can you attack this?

```
int x;
char *buf = ( char * )malloc( 50 );
x = adversary-controlled-value;
If ( x < 50 ) {
    snprintf( buf, x, “%s”, adversary-controlled-input );
}
```

Integer Overflows

- Can you attack this?
  - Unfortunately, we can – snprintf casts to unsigned
  - Negative value becomes a large positive value

```
int x;
char *buf = ( char * )malloc( 50 );
x = adversary-controlled-value;    // negative value
If ( x < 50 ) {                    // passes this condition
    snprintf( buf, x, “%s”,        // second arg ‘x’ to snprintf is unsigned
        adversary-controlled-input );  // too long input
}
```

Integer Overflows

- Can you attack this?
  - Unfortunately, we can – have to compute "size" correctly

```
int x;
char *buf = ( char * )malloc( 50 );
x = adversary-controlled-value;     // negative value
If ( x < 50 ) {                      // passes this condition
    snprintf( buf, x, "%s",          // 'x' becomes a large positive value - overflow
        adversary-controlled-input );  // too long input
}
```

Fundamental Problem?

- What is the fundamental problem that causes type errors?

Fundamental Problem?

- What is the fundamental problem that causes type errors?
  - Type casting – create pointer of different type
  - Temporal errors – change type of memory region
- These enable the same memory region to be referenced as multiple types
  - Enabling exploitable type errors
- Resulting exploitable flaws
  - Misinterpret the size of the region (downcast)
  - Data misinterpreted as a pointer (type confusion)
  - Data values misinterpreted (integer overflow)

Safety from Type Errors

- Type safety
  - Memory region is only referenced by pointers of one type
  - Corresponding to the type of the memory region allocation
- Memory safety (for regions of multiple types)
  - Memory region may be referenced by pointers of more than one type
  - Semantics of all references correspond to allocation and consistent use of the memory region
  - Think about "question" types in the project

Obvious Solution in C

- So, do you see an "obvious" solution to prevent exploitable type errors?

Obvious Solution in C

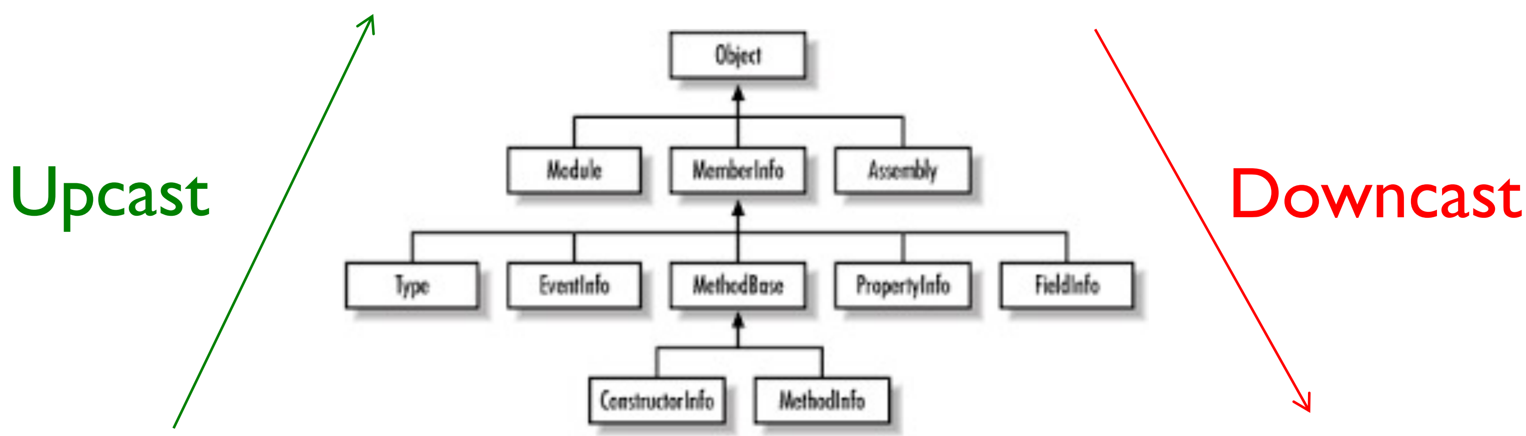
- So, do you see an “obvious” solution to prevent exploitable temporal errors?
  - No type casts? May be hard to ensure that

Obvious Solution in C

- So, do you see an "obvious" solution to prevent exploitable temporal errors?
  - What can we do to prevent the misinterpretation of data even if we allow type casts?

Safe Casts

- Only allow "upcasts" for type casts
  - A "downcast" from a parent data type to a child data type
    - Adds more fields – may allow overflow
  - An "upcast" from a child data type to a parent data type
    - Reduces fields – no overflow possible, fields are same type



Other Ideas

- Can you think of any other ways to prevent type error exploits?
  - May be a little crazy

Alternatives

- Hypothesis: Validate type consistency on casts
  - At runtime – but can be expensive (>100%)
  - Maybe type casts are not super-common in your program
  - Prove some type casts are safe statically?
- Hypothesis: Use type-specific allocation
  - Only helps for temporal errors
  - Unless do validity checks also

Take Away

- Flexible type casting in C permits type errors
  - So, type errors have become common, especially now that defenses for spatial errors have improved
- Exploiting type errors involves exploiting a reference to a memory region interpreted in multiple ways (using multiple types)
  - Set data value, but use as a pointer
- Preventing type errors is not so easy (except upcasts)
  - And, a bit more expensive than people will accept yet