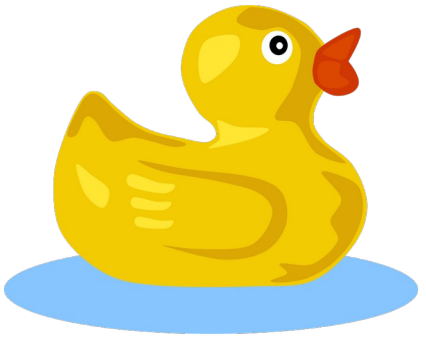
CS 430 Spring 2022

Mike Lam, Professor



$$\text{TEq}\ \frac{\Gamma \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1\ \text{`==`}\ e_2 : \textbf{bool}}$$

Types and Checking

261 Review

- Observation: the type of a variable is largely lost by the time a program runs on a particular hardware system
  - Variables are stored in registers or memory locations
  - Computation is encoded using machine-code instructions
  - Everything must match!
    - Operand sizes (e.g., 32-bit vs. 64-bit)
    - Integer vs. floating-point numbers
    - Signed vs. unsigned integers
    - ASCII vs. Unicode characters
  - Types are an abstraction to help track and manage the details
    - Example: use "`subq`" instruction for "`int64_t`" variables

Type Systems

- Type system
  - Rules about valid types, type compatibility, and how data values can be used
  - Enforced by compiler or runtime system
- Benefits of a robust type system
  - Earlier error detection
  - Better documentation
  - Increased modularization

Data Types

- Data type: collection of values and associated operations
  - Descriptor: collection of a variable's attributes, including its type
- Primitive data types
  - Integer, floating-point, complex, decimal, boolean, character
- User-defined data types
  - Structured: arrays, tuples, maps, records, unions
  - Ordinal: enumerations, subranges
  - Pointers and references

Data Types

- Primitive data types
  - Integer: signed vs. unsigned, two's complement, arbitrary sizes
    - Tradeoff: storage/speed vs. range
  - Floating-point: IEEE standard (sign bit, exponent, significand), precision, rounding error
    - Tradeoff: storage/speed vs. accuracy, precision vs. range
  - Character: ASCII, Unicode, UTF-8, and UTF-16 (variable-length), UTF-32 (fixed-length)
    - Tradeoff: expressivity vs. storage space and processing time
  - Boolean: 0 (false) or 1 (true); usually byte-sized
  - Complex: pairs of floats (real and imaginary)
  - Decimal: binary coded decimal (4 bits per digit)

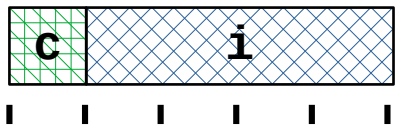
User-Defined Data Types

- Structured
  - Arrays and lists: indexed sequences of elements
  - Tuples: fixed-length sequence of elements
  - Associative arrays: mapping from keys to values (often w/ hashing)
  - Records: (name, type) pairs, dot notation, a.k.a. "structs"
  - Unions: different types at runtime, tag/discriminant, safety issues
- Ordinal (value <=> integer mapping)
  - Booleans and characters
  - Enumerations: subset of constants
  - Subranges: contiguous subsequence of another ordinal type

Data Types

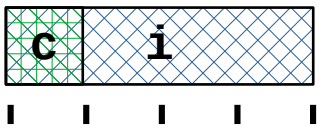
- Product types: cross product of other types
  - Like a `struct` in C ("*both/and*") - must be large enough for "one of each"
  - Number of unique values is **product** of composed types
- Sum types: union of other types
  - Like a `union` in C ("*either/or*") - must be large enough for largest component
  - Number of unique values is **sum** of composed types

```
/* product type */
struct {
  char c;
  int i;
} x;
```



(5 bytes)

```
/* sum type */
union {
  char c;
  int i;
} x;
```



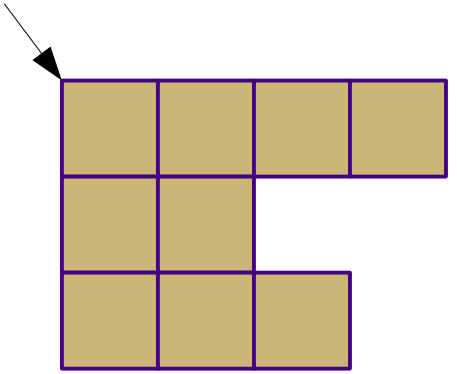
(4 bytes)

Arrays and Lists

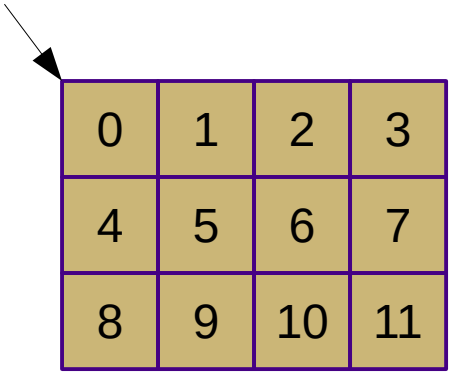
- Arrays
  - Usually homogeneous (with fixed element width)
  - Usually fixed-length
  - Usually static or fixed stack/heap-dynamic
  - Calculating index offsets: `base + index * (element_size)`
- Lists
  - Sometimes heterogeneous
  - Usually variable-length
  - Usually stack-dynamic or heap-dynamic
  - In functional languages: usually defined as `head:tail`

Multidimensional Arrays

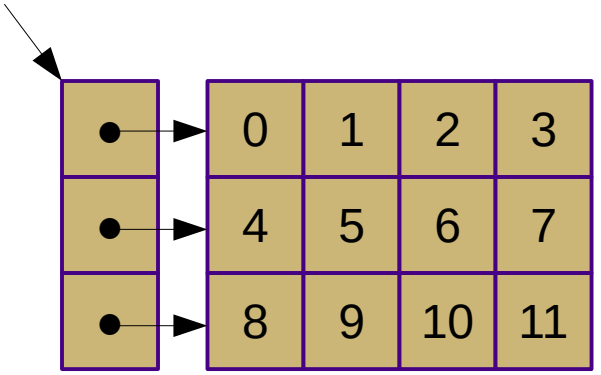
- Multidimensional arrays
  - True multidimensional vs. array-of-arrays
  - Row-major vs. column-major
  - Rectangular vs. jagged/ragged
  - Calculating index offsets



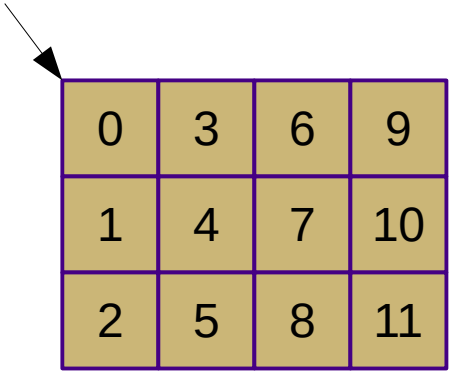
Ragged



Row-major



Row-major array-of-arrays



Column-major

Character Strings

- Strings are often stored as arrays of characters
- Common operations: length calculation, concatenation, slicing, pattern matching
- Questions:
  - Should the language provide special support?
  - Should string length be static or dynamic?
    - How should the length be tracked?
  - Should strings be immutable?
- Tradeoffs: speed vs. convenience
- Buffer/length overruns are a common source of security vulnerabilities

Subtypes

- A subtype is a constrained version of an existing type
  - Values of the subtype can often be used in place of the original, but not vice versa
  - E.g., in Ada: `subtype Small_Int is Integer range 0..100;`

Pointers and References

- Pointer: memory address or **null** / **nil** / **0**
  - Adds a layer of indirection to memory accesses
  - Simplifies creation of dynamic data structures (e.g., trees)
  - Example of a nullable type
- Reference: refers to an object or value in memory
  - Different semantics than pointers (strictly safer)
- Design issues
  - Language support (pointers, references, or both?)
  - Scope and lifetime of pointer/reference and associated value
  - Type restrictions (must match? `void*` allowed?)
  - Arithmetic (generally allowed for pointers, not references)

Pointers

```
int x = 1;
int y[4] = {2, 3, 4, 5};
int *p = &x;
*p = 6;
p = y;
*p = 7;
```

What are the values of x and y at the end?

Pointers

```
int x = 1;
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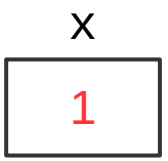

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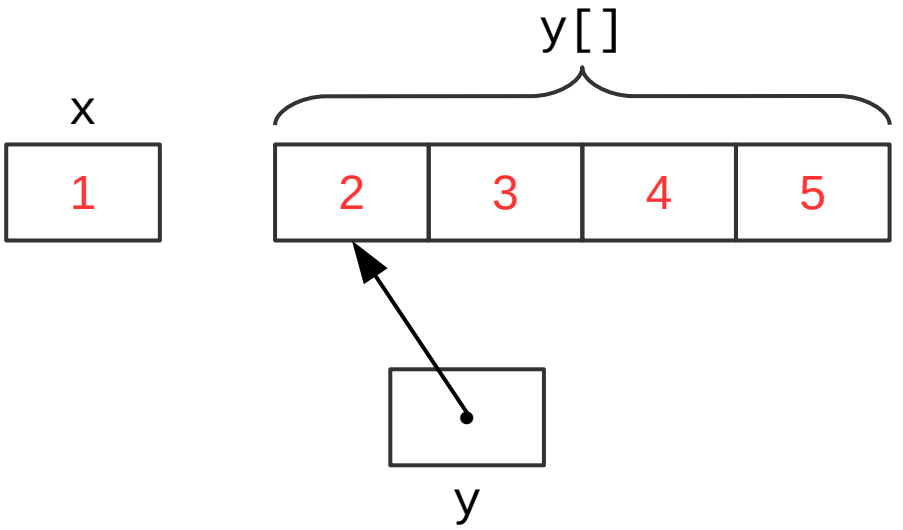

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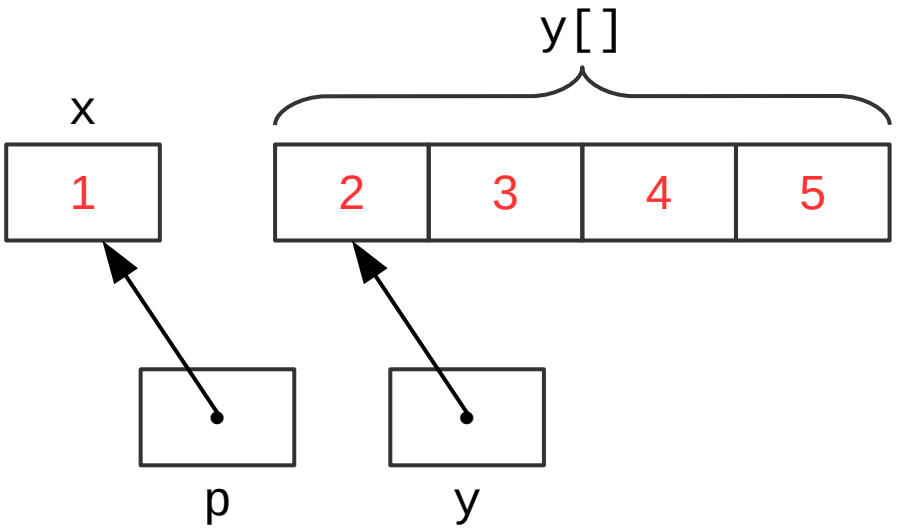

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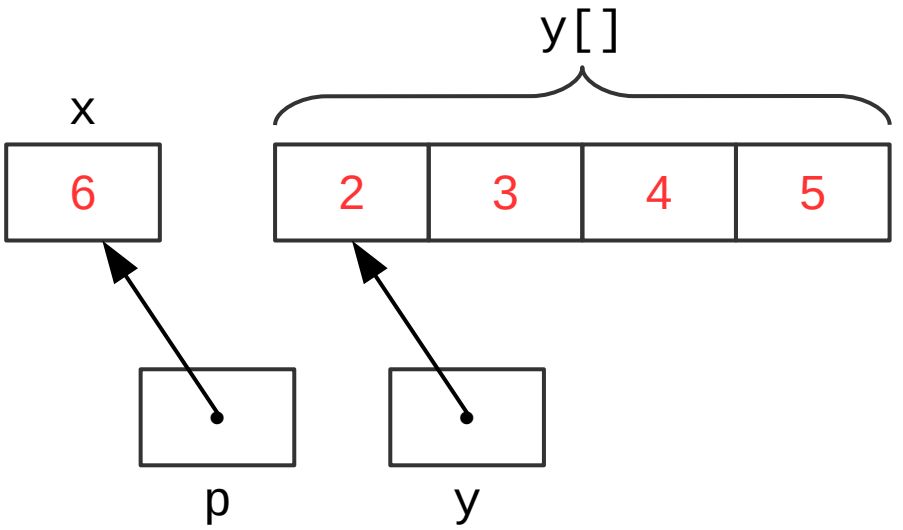

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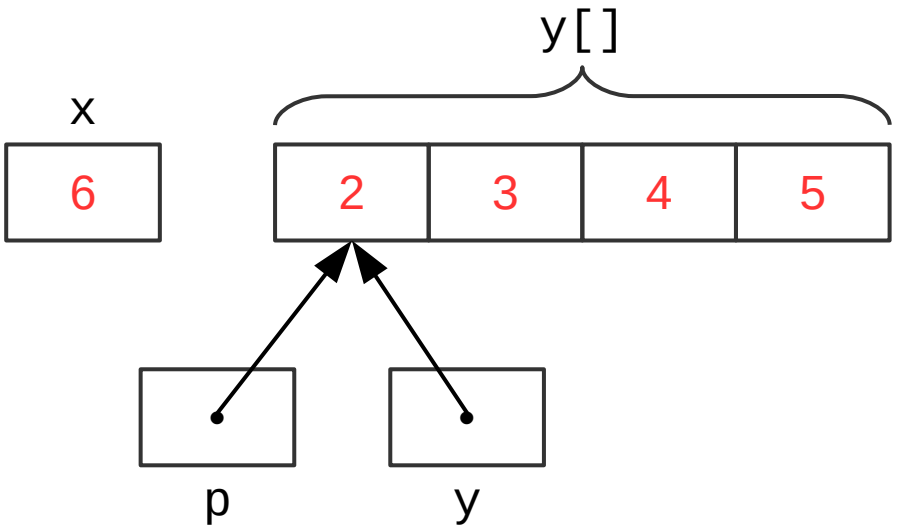

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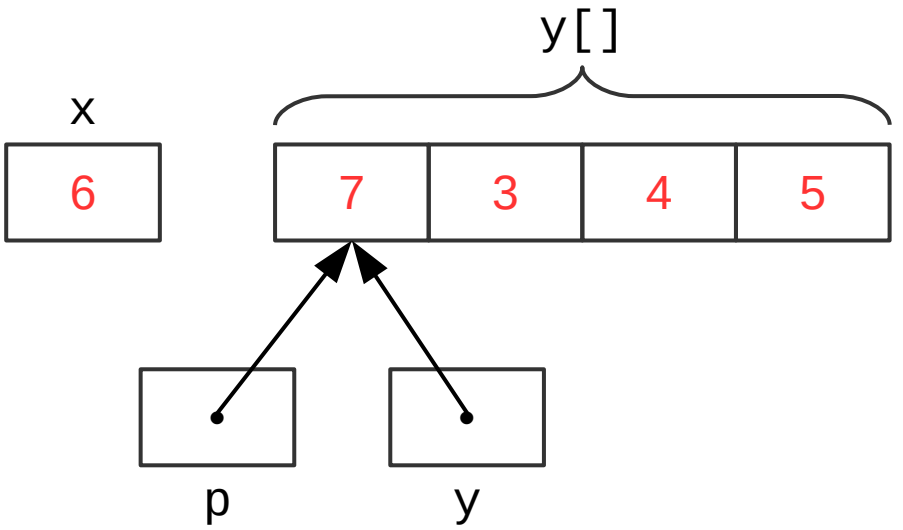

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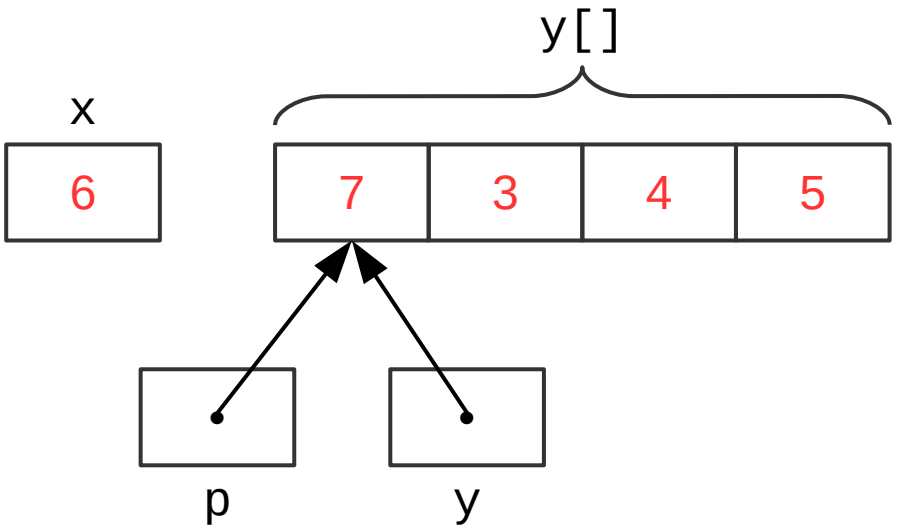


What about this?

```
p++;
*p = 9;
```

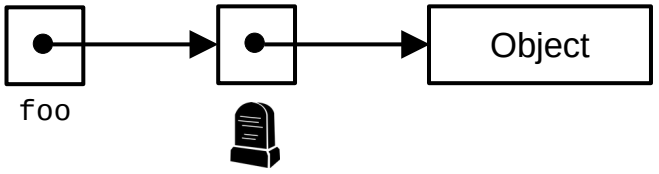
Pointer/Reference Issues

- Dangling pointer: variable is deallocated but pointer remains
  - Dereferencing pointer is invalid (might segfault; might not!)
  - Debuggers (e.g., gdb) can help
- Memory leaks: variable is still allocated but no longer accessible
  - In CPL: lost heap-dynamic variables
  - Memory remains allocated
  - Analysis tools (e.g., Valgrind/Memcheck) can help

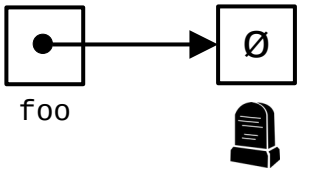
Dangling Pointer Solutions

- Tombstones
  - Extra level of indirection: new access pointer for each object
  - External pointers only point to tombstones
  - When deallocated, tombstone is set to null
  - Causes null pointer dereference if ever used

```
Object *foo = new Object();
```




```
delete foo;
```

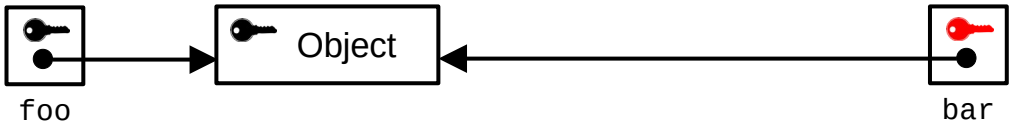


Downside: extra dereference and memory required

Dangling Pointer Solutions

- Locks and keys
  - Pointers are stored as (key, address) pairs
  - Heap variables store key field as well
  - Pointer key and value key are compared for every reference
  - If the keys do not match, the access is invalid

```
Object *foo = new Object();
```

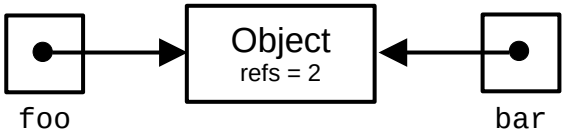


Downside: extra comparison and memory required

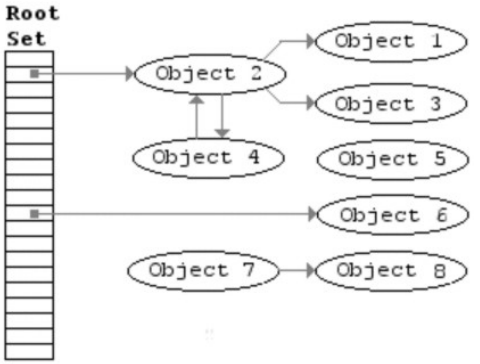
Memory Leak Solutions

- Reference counters
  - Track # of references to an object
  - Deallocate object when counter hits zero

```
Object *foo = new Object();
Object *bar = &foo;
```



- Mark-and-sweep
  - Pause the application (sometimes unnecessary)
  - Initialize indicators for all memory cells to "unmarked"
  - Mark reachable heap memory cells by recursively following pointers from stack and static memory
  - Deallocate unmarked cells
  - Improvements:
    - Generational collection
    - Incremental collection



Type Checking

- Type system
  - Rules about how data values can be used
- Type checking
  - Act of ensuring that the type system is adhered to
    - Ensure that operands are of compatible types
    - Or of equivalent types if coercions aren't allowed
  - Violations are called type errors
    - Usually, type errors are considered to be bugs
    - Sometimes are reported only as warnings

Type Checking

- Language design decisions:
  - Are declarations explicit or implicit?
  - Which types are equivalent?
  - Are type conversions allowed?
  - Can multiple types be used in some places?
  - When does type checking occur?
  - In general, how pedantic is the process?

Type Checking

- Type declarations
  - Explicit: types required
    - E.g., `int x = 5; float y = 4.2;`
  - Implicit: types not required (or even not allowed)
    - E.g., `x = 5; y = 4.2;`
    - Types are bound at assignment
    - However, these types can often be inferred statically
  - Tradeoff: readability vs. writability and expressiveness

Type Checking

- Type equivalence: name vs. structure
  - Named types vs anonymous types
  - Aliased types (e.g., `typedef` in C)
  - Examples:

```
typedef float celsius;
typedef float fahrenheit;

celsius a = 25.7f;
fahrenheit b;

b = a;
```

OK in C

```
typedef struct { int x; } box;
typedef struct { int x; } bin;

box c;
c.x = 5;

bin d;
d = c;
```

NOT OK in C

```
struct { int x; } e;

e = c;
```

NOT OK in C

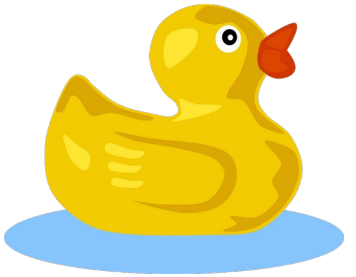
C permits structure equivalence except for records, where it requires name equivalence

Type Polymorphism

- Object-oriented inheritance
  - Example of subtypes
- Parameterized functions
  - Uses generic type variables
  - Example: generic list functions in Haskell
    - E.g., `head : [a] → a` `length : [a] → int`
- Abstract data types
  - Models of generic data structure behavior
  - Implementation is hidden from user
  - Can use parameterized types
    - E.g., a `queue<float>` or `queue<int>`
    - Examples: C++ templates and Java generics

Type Checking

- Static vs. dynamic type checking
  - Static type checking finds type errors at compile time
    - Usually checked by compiler (e.g., Haskell)
  - Dynamic type checking find types errors at run time
    - Usually checked by runtime system (e.g., Ruby, Python)
    - "Duck typing" is a particular form of dynamic typing
      - If an object has a method, you can call it! ("if it quacks like a duck...")
  - Hybrid: some static, some dynamic
    - E.g., C++, Java
  - Tradeoff: overhead vs. flexibility



Type Checking

- Type rules are sometimes expressed using proof notation
  - Premises on top, conclusion at the bottom

$$\text{TDec}\ \frac{}{\vdash \texttt{DEC} : \textbf{int}}$$

"all decimal literals are integers"

$$\text{TTrue}\ \frac{}{\vdash \texttt{true} : \textbf{bool}}$$

"the 'true' literal is a boolean"

$$\text{TAdd}\ \frac{\Gamma \vdash e_1 : \textbf{int} \qquad \Gamma \vdash e_2 : \textbf{int}}{\Gamma \vdash e_1\ \text{`+`}\ e_2 : \textbf{int}}$$

"the result of an addition is an int, as long as both operands are ints"

$$\text{TEq}\ \frac{\Gamma \vdash e_1 : \tau \qquad \Gamma \vdash e_2 : \tau}{\Gamma \vdash e_1\ \text{`==`}\ e_2 : \textbf{bool}}$$

"the result of an equality check is a boolean, as long as both operands are of the same type"

$$\text{TFuncCall}\ \frac{\texttt{ID} : (\tau_1, \tau_2, ..., \tau_n) \rightarrow \tau_r \in \Gamma \qquad \Gamma \vdash e_1 : \tau_1 \qquad \Gamma \vdash e_2 : \tau_2 \qquad ... \qquad \Gamma \vdash e_n : \tau_n}{\Gamma \vdash \texttt{ID}\ \text{`(`}\ e_1, e_2, ..., e_n\ \text{`)`} : \tau_r}$$

"the result of a function call is its return type, as long as all actual parameters match the types of their corresponding formal parameters"

Type Checking

- Strong vs. weak typing
  - Strong typing: all type errors are detected
  - Tradeoff: safety vs. expressiveness
  - Terms often used somewhat loosely
- Evidence of strong typing
  - Static type checking
  - Type inference (even for implicit typing!)
- Evidence of weak typing
  - Type coercions (manual or automatic)
  - Pointer or union types