Why do we study sorting?
- Because we have to
- Because sorting is beautiful
- Example of algorithm analysis in a simple, useful setting

There are $n$ sorting algorithms, how many should we study?
- $O(n)$, $O(\log n)$, ...
- Why do we study more than one algorithm?
  - Some are good, some are bad, some are very, very sad
  - Paradigms of trade-offs and algorithmic design
- Which sorting algorithm is best?
- Which sort should you call from code you write?
Sorting out sorts (see also sortall.cpp)

- **Simple, $O(n^2)$ sorts --- for sorting $n$ elements**
  - Selection sort --- $n^2$ comparisons, $n$ swaps, easy to code
  - Insertion sort --- $n^2$ comparisons, $n^2$ moves, stable, fast
  - Bubble sort --- $n^2$ everything, slow, slower, and ugly

- **Divide and conquer faster sorts: $O(n \log n)$ for $n$ elements**
  - Quick sort: fast in practice, $O(n^2)$ worst case
  - Merge sort: good worst case, great for linked lists, uses extra storage for vectors/arrays

- **Other sorts:**
  - Heap sort, basically priority queue sorting
  - Radix sort: doesn’t compare keys, uses digits/characters
  - Shell sort: quasi-insertion, fast in practice, non-recursive
Selection sort: summary

- Simple to code $n^2$ sort: $n^2$ comparisons, $n$ swaps

```c
void selectSort(tvector<string>& a)
{
    for(int k=0; k < a.size(); k++){
        int minIndex = findMin(a,k,a.size());
        swap(a[k],a[minIndex]);
    }
}
```

- # comparisons: $\sum_{k=1}^{n} k = 1 + 2 + \ldots + n = n(n+1)/2 = O(n^2)$
  - Swaps?
  - Invariant: Sorted, won’t move final position ？？？？
Insertion Sort: summary

- **Stable sort, \(O(n^2)\), good on nearly sorted vectors**
  - Stable sorts maintain order of equal keys
  - Good for sorting on two criteria: name, then age

```cpp
void insertSort(tvector<string>& a)
{
    int k, loc; string elt;
    for(k=1; k < a.size(); k++) {
        elt = a[k];
        loc = k;
        // shift until spot for elt is found
        while (0 < loc && elt < a[loc-1])
        {
            a[loc] = a[loc-1];  // shift right
            loc=loc-1;
        }
        a[loc] = elt;
    }
}
```

| Sorted relative to each other | ?????
Bubble sort: summary of a dog

- For completeness you should know about this sort
  - Few, if any, redeeming features. Really slow, really, really
  - Can code to recognize already sorted vector (see insertion)
    - Not worth it for bubble sort, much slower than insertion

```cpp
void bubbleSort(tvector<string>& a) {
    for(int j=a.size()-1; j > 0; j--) {
        for(int k=0; k < j; k++) {
            if (a[k] > a[k+1]) {
                swap(a[k], a[k+1]);
            }
        }
    }
}
```

- “bubble” elements down the vector/array
Summary of simple sorts

- **Selection sort** has $n$ swaps, good for “heavy” data
  - moving objects with lots of state, e.g., ...
    - A string isn’t heavy, why? (pointer and pointee)
    - What happens in Java?
    - Wrap heavy items in “smart pointer proxy”

- **Insertion sort** is good on nearly sorted data, it’s stable, it’s fast
  - Also foundation for Shell sort, very fast non-recursive
  - More complicated to code, but relatively simple, and fast

- **Bubble sort** is a travesty
  - Can be parallelized, but on one machine don’t go near it
    (see quotes at end of slides)
Quicksort: fast in practice

- Invented in 1962 by C.A.R. Hoare, didn’t understand recursion
  - Worst case is $O(n^2)$, but avoidable in nearly all cases
  - In 1997 Introsort published (Musser, introspective sort)
    - Like quicksort in practice, but recognizes when it will be bad and changes to heapsort

```cpp
void quick(tvector<string>& a, int left, int right) {
    if (left < right) {
        int pivot = partition(a, left, right);
        quick(a, left, pivot-1);
        quick(a, pivot+1, right);
    }
}
```

- Recurrence?
Partition code for quicksort

**what we want**

<table>
<thead>
<tr>
<th>&lt;= pivot</th>
<th>&gt; pivot</th>
</tr>
</thead>
<tbody>
<tr>
<td>left</td>
<td>right</td>
</tr>
</tbody>
</table>

**what we have**

```
| ??????????????? |
| left     | right   |
```

**invariant**

```
| <= | > | ?? |
| left | | right |
```

**Easy to develop partition**

```cpp
text
int partition(tvector<string>& a, int left, int right) {
    string pivot = a[left];
    int k, pIndex = left;
    for(k=left+1, k <= right; k++) {
        if (a[k] <= pivot) {
            pIndex++;
            swap(a[k], a[pIndex]);
        }
    }
    swap(a[left], a[pIndex]);
}
```

**loop invariant:**

- statement true each time loop test is evaluated, used to verify correctness of loop
- Can swap into a[left] before loop
- Nearly sorted data still ok
Analysis of Quicksort

• **Average case and worst case analysis**
  - Recurrence for worst case: \( T(n) = T(n-1) + T(1) + O(n) \)
  - What about average? \( T(n) = 2T(n/2) + O(n) \)

• **Reason informally:**
  - Two calls vector size \( n/2 \)
  - Four calls vector size \( n/4 \)
  - ... How many calls? Work done on each call?

• **Partition:** typically find middle of left, middle, right, swap, go
  - Avoid bad performance on nearly sorted data

• **In practice:** remove some (all?) recursion, avoid lots of “clones”
Tail recursion elimination

- If the last statement is a recursive call, recursion can be replaced with iteration
  - Call cannot be part of an expression
  - Some compilers do this automatically

```cpp
void foo(int n) {
    if (0 < n) {
        cout << n << endl;
        foo(n-1);
    }
}

void foo2(int n) {
    while (0 < n) {
        cout << n << endl;
        n = n-1;
    }
}
```

- What if `cout <<` and recursive call switched?
- What about recursive factorial? return n*factorial(n-1);
Merge sort: worst case $O(n \log n)$

- **Divide and conquer --- recursive sort**
  - Divide list/vector into two halves
    - Sort each half
    - Merge sorted halves together
  - What is complexity of merging two sorted lists?
  - What is recurrence relation for merge sort as described?
  \[
  T(n) = 2T(n/2) + O(n)
  \]

- **What is advantage of vector over linked-list for merge sort?**
  - What about merging, advantage of linked list?
  - Vector requires auxiliary storage (or very fancy coding)
Merge sort: lists or vectors

- **Mergesort for vectors**

```
void mergesort(tvector<string>& a, int left, int right)
{
    if (left < right) {
        int mid = (right+left)/2;
        mergesort(a, left, mid);
        mergesort(a, mid+1, right);
        merge(a, left, mid, right);
    }
}
```

- **What’s different when linked lists used?**
  - Do differences affect complexity? Why?

- **How does merge work?**
Mergesort continued

- **Vector code for merge isn’t pretty, but it’s not hard**
  - Mergesort itself is elegant

```cpp
void merge(tvector<string>& a,
            int left, int middle, int right)
// pre:  left <= middle <= right,
// // a[left] <= ... <= a[middle],
// // a[middle+1] <= ... <= a[right]
// post: a[left] <= ... <= a[right]
```

- **Why is this prototype potentially simpler for linked lists?**
  - What will prototype be? What is complexity?
Summary of O(n log n) sorts

- **Quicksort** is relatively straight-forward to code, very fast
  - Worst case is very unlikely, but possible, therefore ...
  - But, if lots of elements are equal, performance will be bad
    - One million integers from range 0 to 10,000
    - How can we change partition to handle this?

- **Merge sort** is stable, it’s fast, good for linked lists, harder to code?
  - Worst case performance is O(n log n), compare quicksort
  - Extra storage for array/vector

- **Heapsort**, more complex to code, good worst case, not stable
  - Basically heap-based priority queue in a vector
Sorting in practice, see libsort.cpp

- Rarely will you need to roll your own sort, but when you do ...
  - What are key issues?

- If you use a library sort, you need to understand the interface
  - In C++ we have STL and sortall.cpp in Tapestry
    - STL has sort, and stable_sort
    - Tapestry has lots of sorts, Mergesort is fast in practice, stable, safe
  - In C the generic sort is complex to use because arrays are ugly
    - See libsort.cpp
  - In Java guarantees and worst-case are important
    - Why won’t quicksort be used?

- Function objects permit sorting criteria to change simply
Standard sorts: know your library

- **Know how to use the STL sorts even if you don't use STL**
  - The `sort` function takes iterators as parameters
  - vectors, strings and other containers: "give me iterators"
    - What about linked-list iterators? Why aren't these "sortable"?

```cpp
string s = ".....";
sort(s.begin(), s.end());
vector<string> vs; // fill vs with values
sort(vs.begin(), vs.end());
```

- **Beware C qsort, vary widely and wildly on different platforms**
  - See `qsort` on Linux/cygwin compared to `g++` on Solaris?
Using STL sorts with tvector

- Include the right header files
  - "tvector.h" for tapestry vectors
  - <algorithm> for STL sorts

- Use STL iterators to get beginning and end of vector

```cpp
tvector<string> vec;
vec.push_back(“hello”);
vec.push_back(“alligator”);
sort(vec.begin(), vec.end());
```

- Can sort strings this way too, but not sets even though they have begin() and end() in STL, why?
  - Don’t support random access, not sortable
In practice: templated sort functions

- Function templates permit us to write once, use several times for several different types of vector
  - Template function “stamps out” real function
  - Maintenance is saved, code still large (why?)

- What properties must hold for vector elements?
  - Comparable using < operator
  - Elements can be assigned to each other

- Template functions capture property requirements in code
  - Part of generic programming
  - Some languages support this better than others (not Java)
Function object concept

- To encapsulate comparison (like operator <) in a parameter
  - Need convention for parameter: name and behavior
  - Enforceable by templates or by inheritance (or both)
    - Sorts don’t use inheritance, `tpq::queue<...>` does

- Name convention: class/object has a method named `compare`
  - Two parameters, the (vector) elements being compared
  - See comparer.h, used in sortall.h and in tpq.h

- Behavior convention: compare returns an int
  - zero if elements equal
  - +1 (positive) if first > second
  - -1 (negative) if first < second
Function object example

class StrLenComp // : public Comparer<string>
{
    public:
        int compare(const string& a, const string& b) const
            // post: return -1/+1/0 as a.length() < b.length()
            {
                if (a.length() < b.length()) return -1;
                if (a.length() > b.length()) return 1;
                return 0;
            }
};
    // to use this:
    StrLenComp scomp;
    if (scomp.compare("hello", "goodbye") < 0) ...
        ➢ We can use this to sort, see sortall.h
        ➢ Call of sort: InsertSort(vec, vec.size(), scomp);
Non-comparison-based sorts

- lower bound: $\Omega(n \log n)$ for comparison based sorts (like searching lower bound)
- bucket sort/radix sort are non-comparison based, faster asymptotically and in practice

- sort a vector of ints, all ints in the range 1..100, how?
  - (use extra storage)
- radix: examine each digit of numbers being sorted
  - One-pass per digit
  - Sort based on digit

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Shell sort

- **Comparison-based, similar to insertion sort**
  - Using Hibbard’s increments (see sortall.h) yields $O(n^{3/2})$
  - Sequence of insertion sorts, note last value of $h$!!

```c
int k, loc, h; string elt;
h = ...;  // set h to $2^p-1$, just less than a.size()
while (h > 0) {
    for(k = h; k < n; k++) {
        elt = a[k];
        loc = k;
        while (h <= loc && elt < a[loc-h]) {
            a[loc] = a[loc-h];
            loc -= h;
        }
        a[loc] = elt;
    }
    h /= 2;
}
```
Jim Gray (Turing 1998)

- Bubble sort is a good argument for analyzing algorithm performance. It is a perfectly correct algorithm. But it's performance is among the worst imaginable. *So, it crisply shows the difference between correct algorithms and good algorithms.*

*(italics ola's)*
Brian Reid (Hopper Award 1982)

Feah. I love bubble sort, and I grow weary of people who have nothing better to do than to preach about it. Universities are good places to keep such people, so that they don't scare the general public.

(continued)
Brian Reid (Hopper 1982)

I am quite capable of squaring N with or without a calculator, and I know how long my sorts will bubble. I can type every form of bubble sort into a text editor from memory. If I am writing some quick code and I need a sort quick, as opposed to a quick sort, I just type in the bubble sort as if it were a statement. I'm done with it before I could look up the data type of the third argument to the quicksort library.

I have a dual-processor 1.2 GHz Powermac and it sneers at your N squared for most interesting values of N. And my source code is smaller than yours.

Brian Reid
who keeps all of his bubbles sorted anyhow.

Good paper, by the way. Well written and actually has something to say.
I have read your article and share your view that Bubble Sort has hardly any merits. I think that it is so often mentioned, because it illustrates quite well the principle of sorting by exchanging.

I think BS is popular, because it fits well into a systematic development of sorting algorithms. But it plays no role in actual applications. Quite in contrast to C, also without merit (and its derivative Java), among programming codes.
Guy L. Steele, Jr. (Hopper ’88)

(Thank you for your fascinating paper and inquiry. Here are some off-the-cuff thoughts on the subject.)

I think that one reason for the popularity of Bubble Sort is that it is easy to see why it works, and the idea is simple enough that one can carry it around in one's head …

continued
Guy L. Steele, Jr.

As for its status today, it may be an example of that phenomenon whereby the first widely popular version of something becomes frozen as a common term or cultural icon. Even in the 1990s, a comic-strip bathtub very likely sits off the floor on claw feet.

... it is the first thing that leaps to mind, the thing that is easy to recognize, the thing that is easy to doodle on a napkin, when one thinks generically or popularly about sort routines.