Merge Sort

Biostatistics 615/815
Lecture 9
Project Assignments

- Project assignments sent out by e-mail
- You have about 8 weeks to complete the project
- First step: come to office hours in the next couple of weeks and sketch out a plan for completing the project!
We need to schedule our midterm

Review Session
  • I propose Thursday, October 19

Mid-term Exam
  • I propose Tuesday, October 24
Choose a partitioning element …

Organize array such that:
  • All elements to the right are greater
  • All elements to the left are smaller

Sort right and left sub-arrays independently
Quick Sort Summary

- Divide and Conquer Algorithm
  - Recursive calls can be “hidden”

- Optimizations
  - Choice of median
  - Threshold for brute-force methods
  - Limiting depth of recursion

- Do you think quick sort is a stable sort?
C Code: QuickSort

```c
void quicksort(Item a[], int start, int stop)
{
    int i;

    if (stop <= start) return;

    i = partition(a, start, stop);
    quicksort(a, start, i - 1);
    quicksort(a, i + 1, stop);
}
```
int partition(Item a[], int start, int stop)
{
    int up = start, down = stop - 1, part = a[stop];

    if (stop <= start) return start;

    while (true)
    {
        while (isLess(a[up], part))
            up++;
        while (isLess(part, a[down]) && (up < down))
            down--;

        if (up >= down) break;
        Exchange(a[up], a[down]);
        up++; down--;
    }

    Exchange(a[up], a[stop]);
    return up;
}
Non-Recursive Quick Sort

```c
void quicksort(Item a[], int start, int stop)
{
    int i, s = 0, stack[64];

    stack[s++] = start;
    stack[s++] = stop;

    while (s > 0)
    {
        stop = stack[--s];
        start = stack[--s];
        if (start >= stop) continue;

        i = partition(a, start, stop);
        if (i - start > stop - i)
        {
            stack[s++] = start; stack[s++] = i - 1;
            stack[s++] = i + 1; stack[s++] = stop;
        }
        else
        {
            stack[s++] = i + 1; stack[s++] = stop;
            stack[s++] = start; stack[s++] = i - 1;
        }
    }
}
```
Selection

Problem of finding the $k^{th}$ smallest value in an array

Simple solution would involve sorting the array
  • Time proportional to $N \log N$ with Quick Sort

Possible to improve by taking into account that only one element must fall into place
  • Time proportional to $N$
C Code: Selection

// Places k\textsuperscript{th} smallest element in the k\textsuperscript{th} position
// within array. Could move other elements.
void select(Item * a, int start, int stop, int k)
{
    int i;

    if (start <= stop) return;

    i = partition(a, start, stop);

    if (i > k) select(a, start, i - 1);
    if (i < k) select(a, i + 1, stop);
}
Merge Sort

- Divide-And-Conquer Algorithm
  - Divides a file in two halves
  - Merges sorted halves
- The “opposite” of quick sort
- Requires additional storage
void mergesort(Item a[], int start, int stop)
{
    int m = (start + stop)/2;

    if (stop <= start) return;

    mergesort(a, start, m);
    mergesort(a, m + 1, stop);
    merge(a, start, m, stop);
}
Merge Pattern N = 21
Merging Sorted Arrays

- Consider two arrays
- Assume they are both in order
- Can you think of a merging strategy?
Merging Two Sorted Arrays

```c
void merge_arrays(Item merged[], Item a[], int N, Item b[], int M)
{
    int i = 0, j = 0, k;

    for (k = 0; k < M + N; k++)
    {
        if (i == N)
        {
            merged[k] = b[j++];
            continue;
        }
```
“In-Place” Merge

- For sorting, we would like to:
  - Starting with sorted halves
    - \(a[\text{start} \ldots m]\)
    - \(a[m + 1 \ldots \text{end}]\)
  - Generate a sorted stretch
    - \(a[\text{start} \ldots \text{end}]\)

- We would like an in-place merge, but…
  - A true “in-place” merge is quite complicated
Abstract In-Place Merge

- For caller, performs like in-place merge
- Creates copies two sub-arrays
- Replaces contents with merged results
C Code: Abstract In-place Merge (First Attempt)

Item extra1[MAX_N];
Item extra2[MAX_N];

void merge(Item a[], int start, int m, int stop)
{
    int i, j, k;

    for (i = start; i <= m; i++)
        extra1[i - start] = a[i];

    for (i = m + 1; i <= stop; i++)
        extra2[i - m - 1] = a[i];

    merge_arrays(a + start, extra1, m - start + 1,
                 extra2, stop - m);
}
C Code: Abstract In-place Merge (Second Attempt)

Item extra[MAX_N];

void merge(Item a[], int start, int m, int stop)
{
    int i, j, k;

    for (i = start; i <= stop; i++)
        extra[i] = a[i];

    for (i = k = start, j = m + 1; k <= stop; k++)
        if (j <= stop && isLess(extra[j], extra[i]) || i > m)
            a[k] = extra[j++];
        else
            a[k] = extra[i++];
}
Avoiding End-of-Input Check

At each point, compare elements \( i \) and \( j \).

Then select the smallest element.

Move \( i \) or \( j \) towards the middle, as appropriate.
C Code: Abstract In-place Merge (Third Attempt!)

```c
void merge(Item a[], int start, int m, int stop)
{
    int i, j, k;

    for (i = start; i <= m; i++)
        extra[i] = a[i];

    for (j = m + 1; j <= stop; j++)
        extra[m + 1 + stop - j] = a[j];

    for (i = k = start, j = stop; k <= stop; k++)
        if (isLess(extra[j], extra[i]))
            a[k] = extra[j--];
        else
            a[k] = extra[i++];
}
```
Merge Sort in Action
Merge Sort Notes

- **Order $N \log N$**
  - Number of comparisons independent of data
  - Exactly $\log N$ rounds
  - Each requires $N$ comparisons

- Merge sort is stable
- Insertion sort for small arrays is helpful
### Sedgewick’s Timings (secs)

<table>
<thead>
<tr>
<th>N</th>
<th>QuickSort</th>
<th>MergeSort</th>
<th>MergeSort*</th>
</tr>
</thead>
<tbody>
<tr>
<td>100,000</td>
<td>24</td>
<td>53</td>
<td>43</td>
</tr>
<tr>
<td>200,000</td>
<td>52</td>
<td>111</td>
<td>92</td>
</tr>
<tr>
<td>400,000</td>
<td>109</td>
<td>237</td>
<td>198</td>
</tr>
<tr>
<td>800,000</td>
<td>241</td>
<td>524</td>
<td>426</td>
</tr>
</tbody>
</table>

Array of floating point numbers; * using insertion for small arrays
Non-Recursive Merge Sort

- First sort all sub-arrays of 1 element

- Perform successive merges
  - Merge results into sub-arrays of 2 elements
  - Merge results into sub-arrays of 4 elements
  - ...

Bottom-Up Merge Sort

Item min(\text{Item } a, \text{Item } b)
{ \text{return isLess}(a,b) \ ? \ a : b; } \}

\textbf{void} \textbf{mergesort}(\text{Item } a[\text{int ]start}, \text{int } stop) \}
{ \text{int } i, m;

\textbf{for} (m = 1; m < stop - start; m += m) \}
\textbf{for} (i = start; i < stop; i += m + m) \}
{ \text{int } from = i;
\text{int } mid = i + m - 1;
\text{int } to = \text{min}(i + m + m - 1, stop);

\text{merge}(a, from, mid, to); \}
}
Merging Pattern for N = 21
## Sedgewick’s Timings (secs)

<table>
<thead>
<tr>
<th>N</th>
<th>QuickSort</th>
<th>Top-Down MergeSort</th>
<th>Bottom-Up MergeSort</th>
</tr>
</thead>
<tbody>
<tr>
<td>100,000</td>
<td>24</td>
<td>53</td>
<td>59</td>
</tr>
<tr>
<td>200,000</td>
<td>52</td>
<td>111</td>
<td>127</td>
</tr>
<tr>
<td>400,000</td>
<td>109</td>
<td>237</td>
<td>267</td>
</tr>
<tr>
<td>800,000</td>
<td>241</td>
<td>524</td>
<td>568</td>
</tr>
</tbody>
</table>

Array of floating point numbers
Automatic Memory Allocation

- Defining large static arrays is not efficient
  - Often, program will run on smaller datasets and the arrays will just waste memory

- A better way is to allocate and free memory as needed

- Create a “wrapper” function that takes care of memory allocation and freeing
Merge Sort,  
With Automatic Memory Allocation

Item * extra;

void sort(Item a[], int start, int stop)
{
    // Nothing to do with less than one element
    if (stop <= start) return;

    // Allocate the required extra storage
    extra = malloc(sizeof(Item) * (stop - start + 1));

    // Merge and sort the data
    mergesort(a, start, stop);

    // Free memory once we are done with it
    free(extra);
}
Today ...

- Quick Sort
- Merge Sort
- Unraveled Recursive Sorts
- Contrasting approaches to divide and conquer
Sorting Summary

- Simple $O(N^2)$ sorts for very small datasets
  - Insertion, Selection and Bubblesort

- Improved, but more complex sort
  - Shell sort

- Very efficient $N \log N$ sorts
  - Quick Sort (requires no additional storage)
  - Merge Sort (requires a bit of additional memory)
Sorting Indexes

- Generating an index is an alternative to sorting the raw data
- Allows us to keep track of many different orders
- Can be faster when items are large

How it works:
- Leaves the array containing the data unchanged
- Generates an array where position $i$ records position of the $i^{th}$ smallest item in the original data
Example:
Indexing with Insertion Sort

```c
void sort(int index[], Item a[], int start, int stop)
{
    int i, j;

    for (i = start; i <= stop; i++)
        index[i] = i;

    for (i = start + 1; i <= stop; i++)
        for (j = i; j > start; j--)
            if (isLess(a[index[j]], a[index[j-1]]))
                Exchange(index[j-1], index[j])
            else
                break;
}
```
Next Lecture: An Alternative to Sorting

- We’ll see how to organize data so that it can be searched …

- And so the complexity of searching and organizing the data is less than $N \log N$

- Cost: Doing this will require additional memory
Recommended Reading

- For QuickSort
  - Sedgewick, Chapter 7

- For MergeSort
  - Sedgewick, Chapter 8