



CUDA 4 Prefix Sums

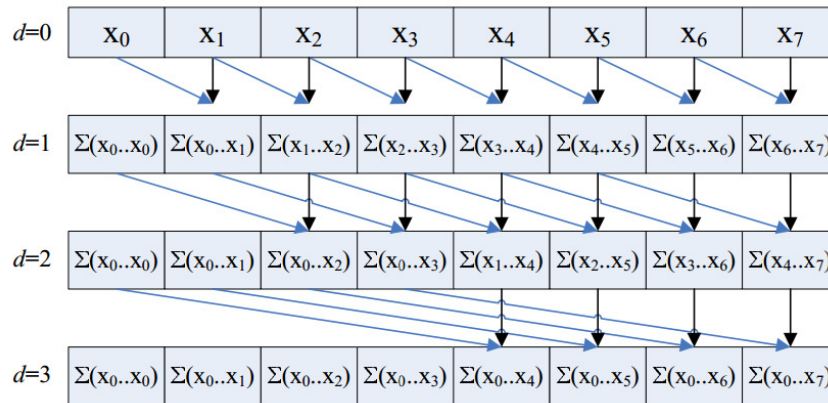
CS121 Parallel Computing
Fall 2021



Prefix sum

- ❑ Given an array $[x_0, x_1, \dots, x_{n-1}]$, output sums of prefixes of the array, $[x_0, x_0+x_1, \dots, x_0+\dots+x_{n-1}]$.
- ❑ Also called inclusive “scan”.
- ❑ Has a large number of applications in parallel algorithms.
 - ❑ Histograms, counting sort, radix sort, stream compaction, string comparison, tree algorithms, polynomial interpolation, recurrences, etc.
- ❑ Trivial sequential algorithm.
 - ❑ Does $O(n)$ operations in $O(n)$ time.
- ❑ Can replace sum with any associative operator.
 - ❑ \oplus is associative if $a \oplus (b \oplus c) = (a \oplus b) \oplus c$.

Parallel prefix sum (naive)

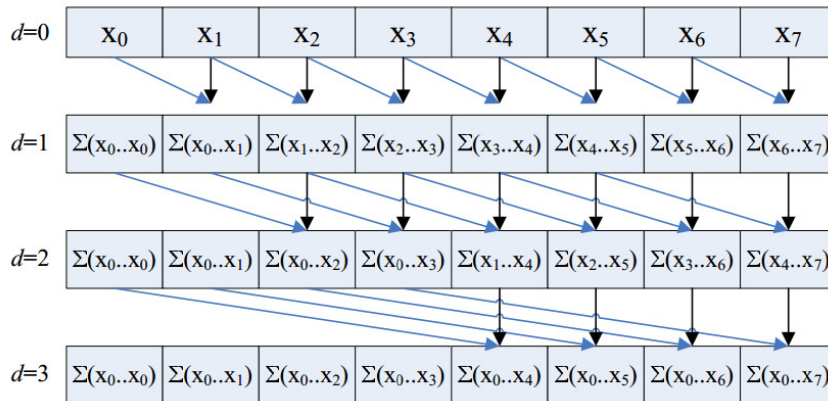


```
for (i = 1; i < log(n); i++)
  for all tid in parallel
    if (tid >= 2i)
      sum[out][tid] = sum[in][tid-2i-1]
      + x[in][tid]
    else
      sum[out][tid] = sum[in][tid]
  swap in, out
```

Parallel Prefix Sum (Scan) with CUDA, Mark Harris

- Map one thread to each element.
- $\log_2 n$ iterations (assume n is power of 2).
 - Set stride to 1, 2, 4, ..., n .
 - Threads $>$ stride add value from stride below to itself.
- Two output buffers $\text{sum}[\text{in}]$, $\text{sum}[\text{out}]$. Initially $\text{in}=0$, $\text{out}=1$. Swap after each iteration.
 - Single buffer would have race condition (how?).

Work analysis



```

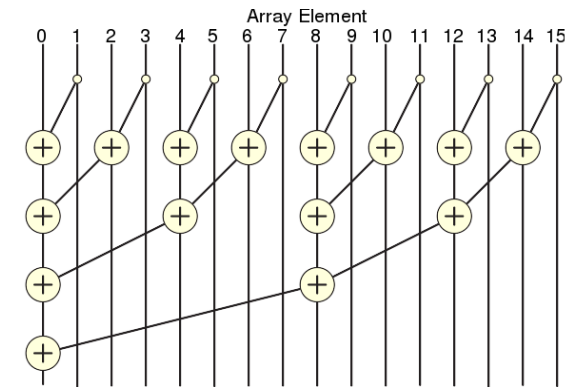
for (i = 1; i < log(n); i++)
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Parallel Prefix Sum (Scan) with CUDA, Mark Harris

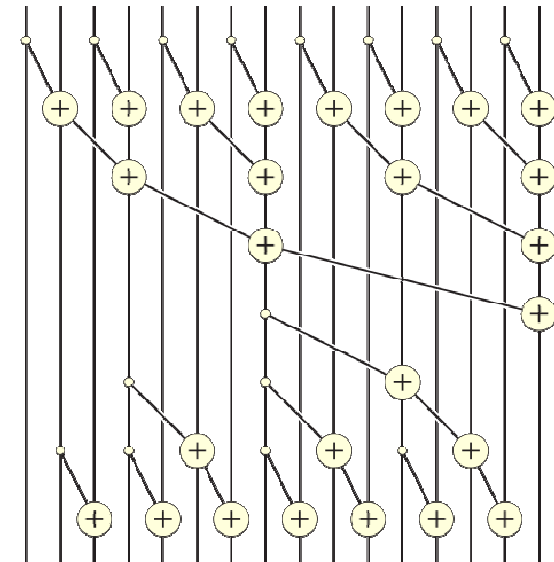
- Number of operations in iteration i is $n - \text{stride}(i)$.
- Total number of operations is $(n-1) + (n-2) + (n-4) + \dots + (n-n/2) = O(n \log n)$.
- Sequential (and optimal) complexity is $O(n)$.
- Extra $O(\log n)$ factor complexity really matters in practice.
 - 20 times slower for $n = 1\text{M}$!

Efficient parallel prefix sum

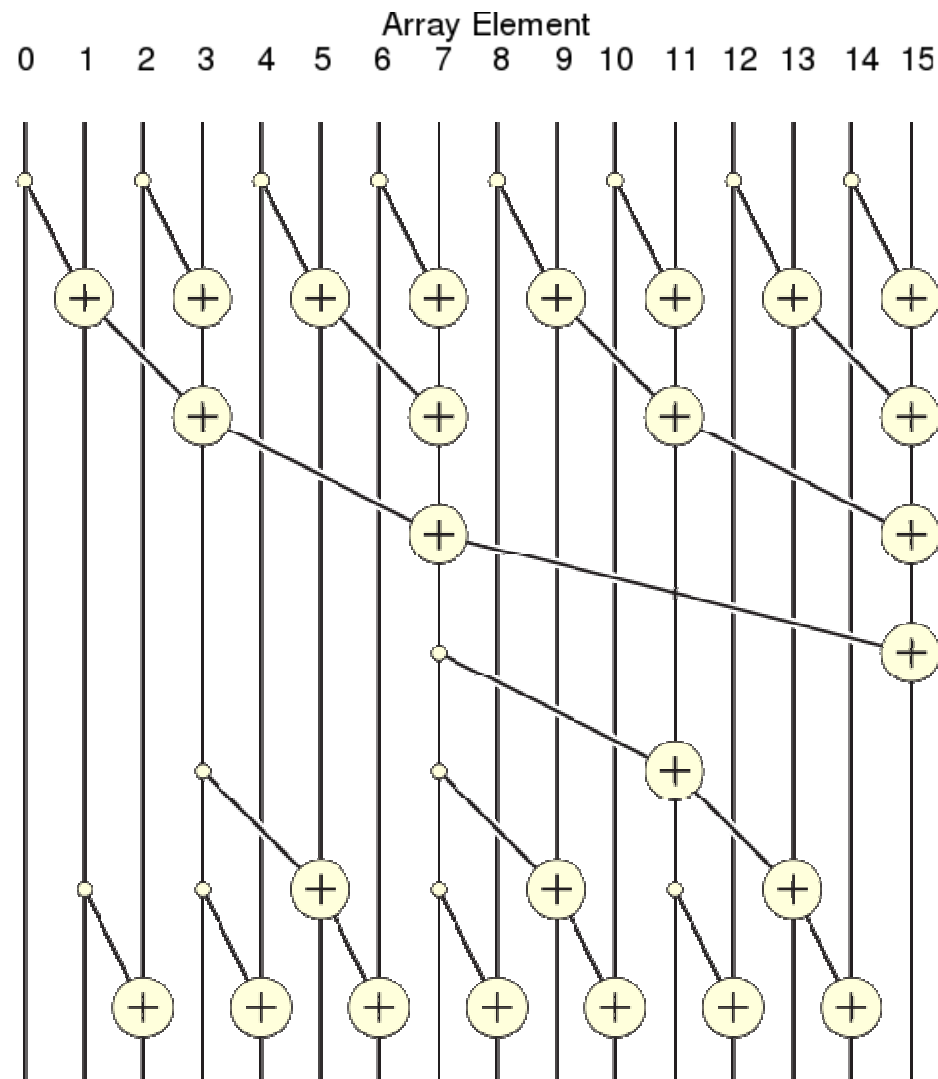
- ❑ Want algorithm to do $O(n)$ work.
- ❑ Recall the parallel reduction algorithm, which does $O(n)$ work.
- ❑ Efficient algorithm does a reduction, followed by the reduction “in reverse”.
 - ❑ Call these the up-sweep and down-sweep phases, resp.



Prefix sum (Brent-Kung)



Efficient parallel prefix sum

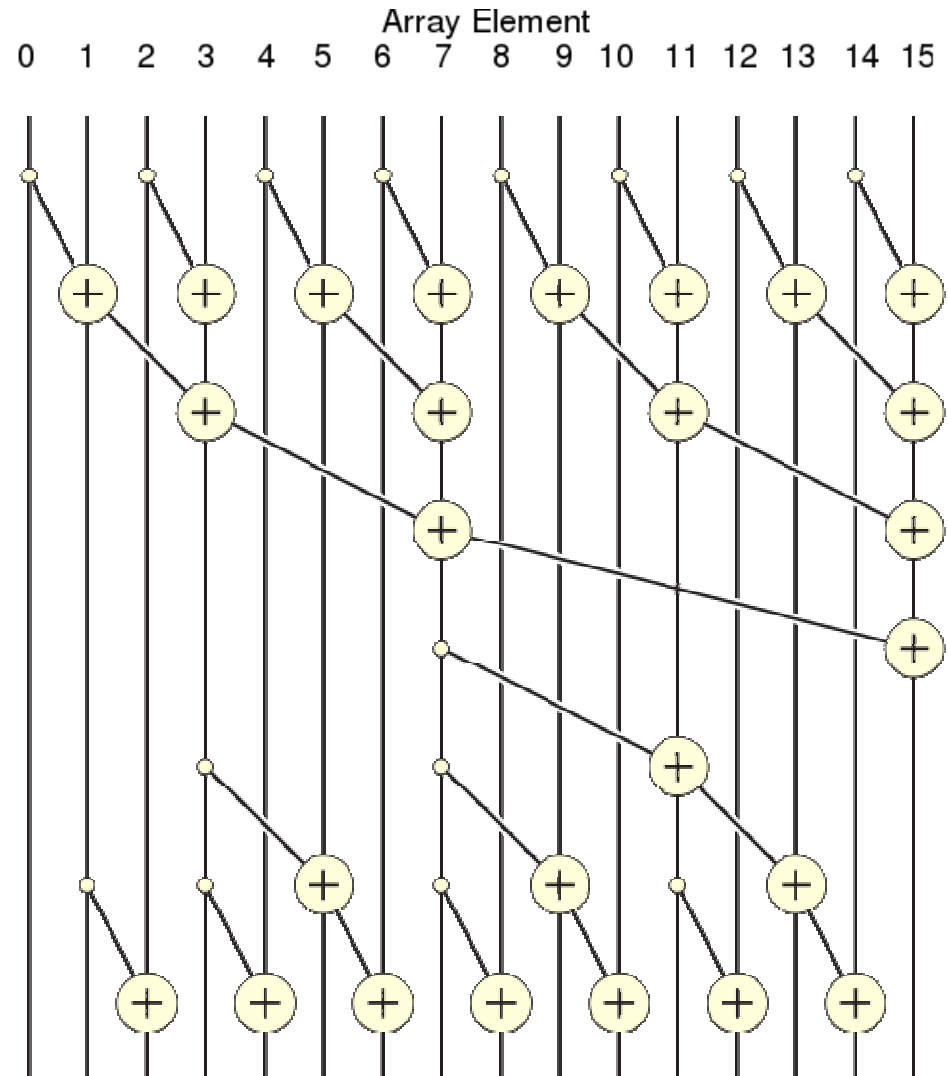


Efficient parallel prefix sum

```
int stride = 1;
while (stride <= blockDim.x) {
    int i = 2*stride*(threadIdx.x+1)-1;
    if (i < 2*blockDim.x)
        sum[i] += sum[i-stride];
    stride *= 2;
    __syncthreads();
}

int stride = blockDim.x/2;
while (stride > 0) {
    int i = 2*stride*(threadIdx.x+1)-1;
    if (i+stride < 2*dimBlock.x)
        sum[i+stride] += sum[i];
    stride /= 2;
    __syncthreads();
}
```

- A thread block computes prefix sum of array sum in shared memory.
 - Size of sum is $2 \times (\text{block size})$.
 - In example, block size = 8.
- In down sweep, threads 0 to (block size) / stride – 1 work in iteration stride.
- In up sweep, threads 0 to (block size) / (2*stride) – 1 work in iteration stride.

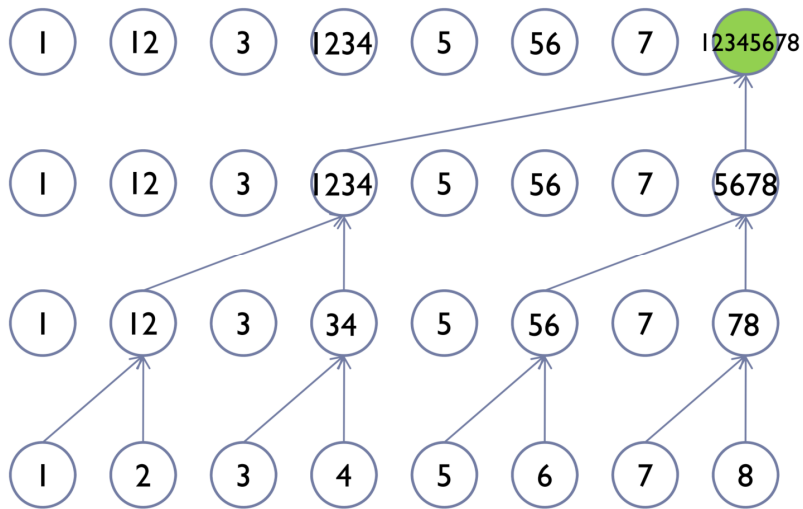




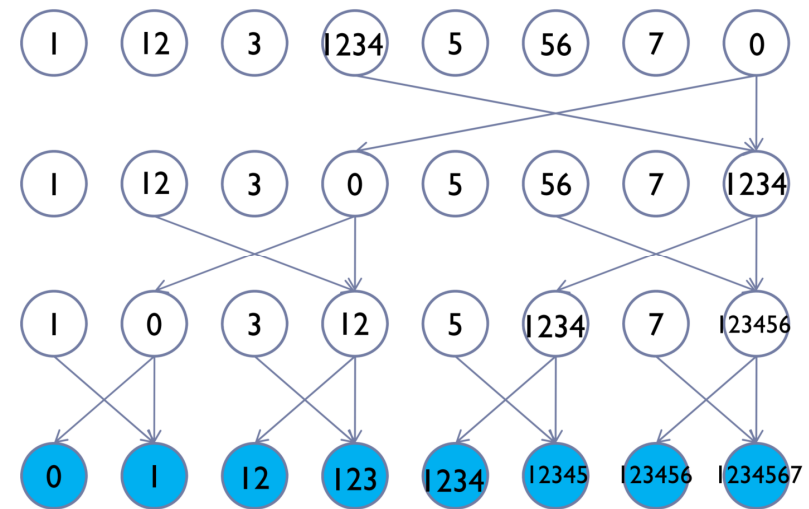
Exclusive scans

- Just like a normal scan, except each input value shouldn't include itself in its output.
 - Ex $[1, 2, 3, 4] \Rightarrow [0, 1, 3, 6]$.
- Up-sweep is the same as in inclusive scan.
- But during down-sweep, first zero out the final output value.
- Then follow a half butterfly pattern downwards.
 - Each right child sums its parents' values.
 - Each left child takes its parent's value.

Exclusive scans



Up-sweep



Down-sweep

Up-sweep (reduce):

```

1: for  $d = 0$  to  $\log_2 n - 1$  do
2:   for all  $k = 0$  to  $n - 1$  by  $2^{d+1}$  in parallel do
3:      $x[k + 2^{d+1} - 1] \leftarrow x[k + 2^d - 1] + x[k + 2^{d+1} - 1]$ 
  
```

Down-sweep:

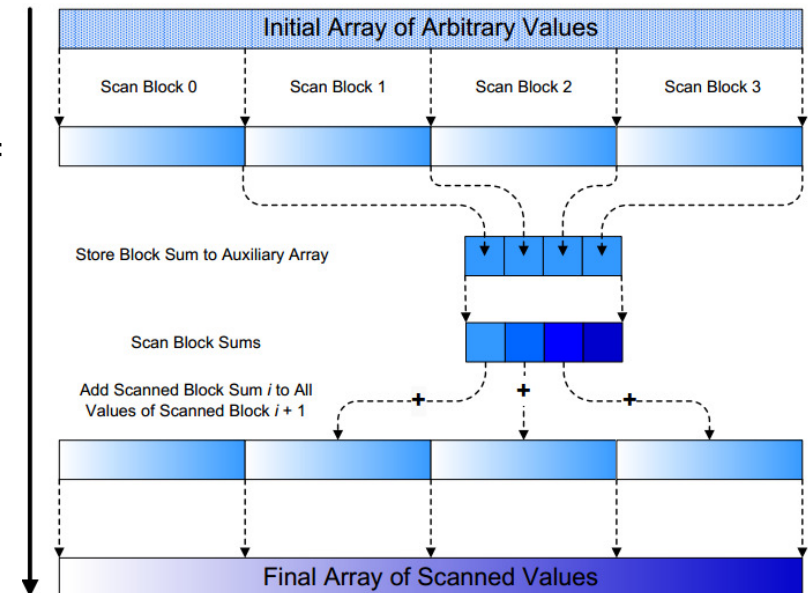
```

1:  $x[n - 1] \leftarrow 0$ 
2: for  $d = \log_2 n - 1$  down to  $0$  do
3:   for all  $k = 0$  to  $n - 1$  by  $2^{d+1}$  in parallel do
4:      $t \leftarrow x[k + 2^d - 1]$ 
5:      $x[k + 2^{d+1} - 1] \leftarrow x[k + 2^{d+1} - 1]$ 
6:      $x[k + 2^d - 1] \leftarrow t + x[k + 2^{d+1} - 1]$ 
  
```

Source: <http://courses.me.berkeley.edu/ME290R/S2009/lectures/lec15.PDF>

Arbitrary input size

- The inclusive scan algorithm only works for array size $\leq 2 \times (\text{block size})$.
- For bigger inputs, break it into segments of size $2 \times (\text{block size})$.
- Compute prefix sum on each segment using block algorithm.
- Copy sum of whole segment (stored in `sum[blockDim.x-1]`) to `segment_sum` array.
- Do this for all blocks until they all finish.
 - Ensure blocks finished by ending kernel.
- Compute prefix sum of `segment_sum` array in a second kernel.
- In a third kernel, distribute prefix sums to each segment.
 - Segment increases all values by prefix sum received.



Bank conflicts

- Recall memory address x stored at $x \% n$ if shared memory has n banks.
 - Current GPUs have 32 banks.
- Current algorithm has many bank conflicts, causing serialized accesses.

bank 0	0	4	8	12	16
bank 1	1	5	9	13	17
bank 2	2	6	10	14	18
bank 3	3	7	11	15	19

16 banks, stride = 1. 2 way bank conflicts

tid	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
i	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31
bank	1	3	5	7	9	11	13	15	1	3	5	7	9	11	13	15

16 banks, stride = 2. 4 way bank conflicts

tid	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
i	3	7	11	15	19	23	27	31	35	39	43	47	51	55	59	63
bank	3	7	11	15	3	7	11	15	3	7	11	15	3	7	11	15

```
...
int i = 2*stride*
    (threadIdx.x+1)-1;
if (i < 2*blockDim.x)
    sum[i] += sum[i-
        stride];
...
```

Removing bank conflicts

- Remove bank conflicts by padding the sum array.
- Store i 'th item at address $i + \text{floor}(i / (\# \text{ banks}))$ instead of address i .
 - Do this for reads and writes.
 - Waste some space ($\sim 3\%$ with 32 banks), but get faster performance.
- Ex 4 banks.

array	0	1	2	3	4	5	6	7	8	9	10	11		
padded array	0	1	2	3	P	4	5	6	7	P	8	9	10	11

- Padding is a general strategy for removing bank conflicts, though exact scheme depends on problem.

Removing bank conflicts

16 banks, stride = 2. 4 way bank conflicts

tid	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
i	3	7	11	15	19	23	27	31	35	39	43	47	51	55	59	63
bank	3	7	11	15	3	7	11	15	3	7	11	15	3	7	11	15

16 banks, stride = 2, $i' = i + \text{floor}(i / \# \text{ banks})$. No bank conflicts

tid	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
i'	3	7	11	15	20	24	28	32	37	41	45	49	54	58	62	66
bank	3	7	11	15	4	8	12	0	5	9	13	1	6	10	14	2

Segmented scan

- Sometimes need to scan several segments at once.
 - Many applications, e.g. sparse matrix vector multiplication, processor allocation, etc.
- Ex $[1\ 2\ 3\ 4]\ [6\ 5]\ [1\ 3\ 5] \Rightarrow [0\ 1\ 3\ 6]\ [0\ 6]\ [0\ 1\ 4]$.
- If there are m segments and we do m scans, each of size n , then total parallel time is $O(m \log n)$.
- Segmented scan does all the scans in $O(\log mn)$ parallel time.
- Use flags array to mark the start of segments.
 - Ex Array for example above is $[1\ 0\ 0\ 0\ 1\ 0\ 1\ 0\ 0]$.
- Define new array of pairs, $c_i = [f_i, x_i]$.
 - f_i and x_i are the initial flag and value at index i .
- Define new associative operator \odot on c_i
$$c_1 \odot c_2 = [f_1, x_1] \odot [f_2, x_2] = \begin{cases} [f_1 \mid f_2, x_1 + x_2], & f_2 = 0 \\ [f_1 \mid f_2, x_2], & f_2 = 1 \end{cases}$$
 - First case is when x_1, x_2 are in same segment, second is when x_2 is in new segment.
- Do a scan as before over array c_i with operator \odot .

Application: compaction

- Create array containing elements of input array satisfying a condition.
- **Ex** Move all odd numbers in A to front of *output*.
 - Create filter array that's 1 if element satisfies condition.
 - Prefix sum the filter array.
 - For each element, if it satisfies condition, move it to index given by prefix sum.

$A =$ [1 3 2 4 8 6 5 4 9 7 3]
filter = [1 1 0 0 0 0 1 0 1 1 1]
sums = [1 2 2 2 2 2 3 3 4 5 6]
output = [1 3 5 9 7 3]



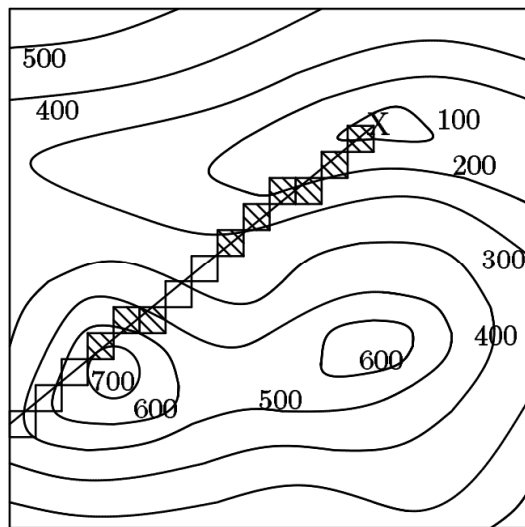
Application: string comparison

- Compare two strings alphabetically.
- Ex $\text{parallax} < \text{parallel}$.
- Let strings be S, T . Let $S[i], T[i]$ denote i 'th letter of S, T .
- ❖ In parallel, i 'th processor compares $S[i]$ to $T[i]$.
 - ❖ If $S[i] > T[i]$, set $A[i] = 1$.
 - ❖ If $S[i] = T[i]$, set $A[i] = 0$.
 - ❖ If $S[i] < T[i]$, set $A[i] = -1$.
 - ❖ If $S[i]$ or $T[i]$ doesn't exist, set $A[i] = 0$.
- ❖ Compact A to remove all 0's.
- ❖ If $\text{output}[1] = 1$, then $S > T$.
- ❖ If $\text{output}[1] = -1$, then $T > S$.
- ❖ If output is empty, then $S = T$.
- Ex $S = \text{parallax}, T = \text{parallel}, A = [0, 0, 0, 0, 0, 0, -1, 1], \text{output} = [-1, 1]$, so $T > S$.

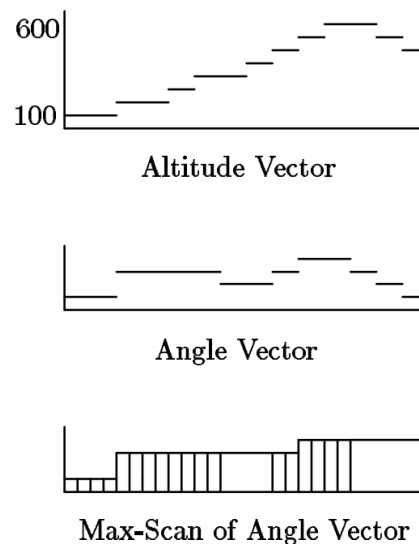
Application: line of sight

```

procedure line-of-sight(altitude)
  in parallel for each index  $i$ 
     $\text{angle}[i] \leftarrow \arctan(\text{scale} \times (\text{altitude}[i] - \text{altitude}[0]) / i)$ 
  max-previous-angle  $\leftarrow$  max-prescan(angle)
  in parallel for each index  $i$ 
    if ( $\text{angle}[i] > \text{max-previous-angle}[i]$ )
       $\text{result}[i] \leftarrow \text{"visible"}$ 
    else
       $\text{result}[i] \leftarrow \text{not "visible"}$ 
  
```



Altitude Map



Ray Vectors

- Given a contour map, an observation point X and a direction, want to know which points are visible.
- First, draw a line from X in the observing direction and record the altitudes along the line in an altitude vector.
- Then for each point calculate its angle, based on its altitude and distance from X.
- Then do a max-scan over the angle vectors.
- A point is visible iff its angle is larger than all the preceding angles.