CENG 4480

Embedded System Development & Applications

Lec 04: Direct Conv

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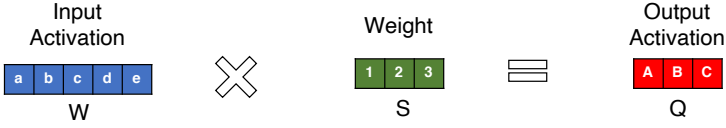
Overview

1. Loop Reordering
2. Direct Convolution
3. Dataflow Optimization

Loop Reordering

1D Convolution Example



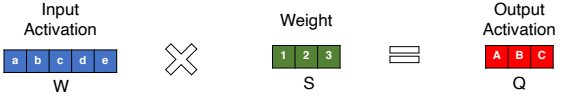

```
for(q=0; q<Q; q++){
  for (s=0; s<S; s++){
    OA[q] += IA[q+s] * W[s];
  }
}
```

Output Stationary (OS) Dataflow

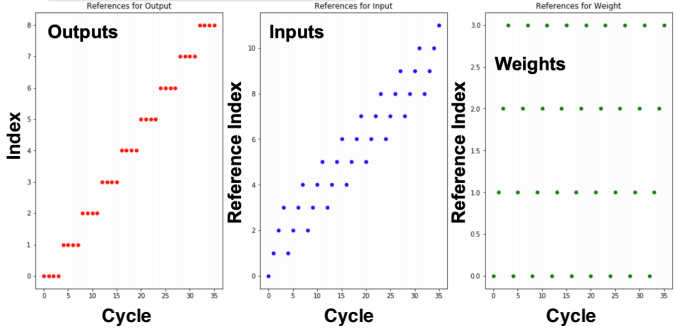
```
for (s=0; s<S; s++){
  for(q=0; q<Q; q++){
    OA[q] += IA[q+s] * W[s];
  }
}
```

Weight Stationary (WS) Dataflow

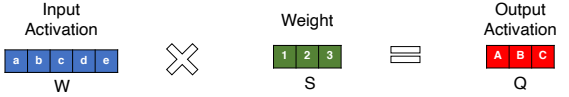
Buffer Access Pattern 1: Output Stationary



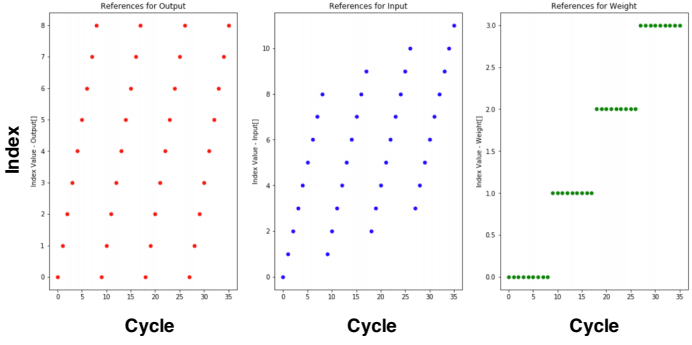

```
for(q=0; q<Q; q++){  // Q =9
  for (s=0; s<S; s++){  // S=4
    OA[q] += IA[q+s] * W[s];
  }
}
```



Buffer Access Pattern 2: Weight Stationary



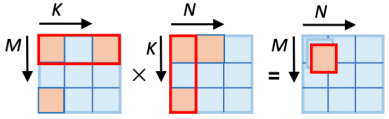

```
for (s=0; s<S; s++){// S=4
  for(q=0; q<Q; q++){// Q =9
    OA[q] += IA[q+s] * W[s];
  }
```



2D Convolution Example

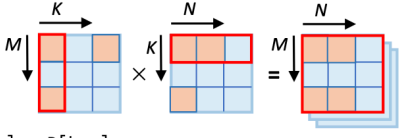
Inner-product dataflow

```
for m in 0..M
 for n in 0..N
  for k in 0..K
   C[m,n] += A[m,k] * B[k,n]
```



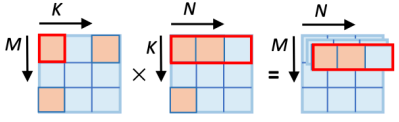
Outer-product dataflow

```
for k in 0..K
 for m in 0..M
  for n in 0..N
   C[m,n] += A[m,k] * B[k,n]
```



Row-based dataflow

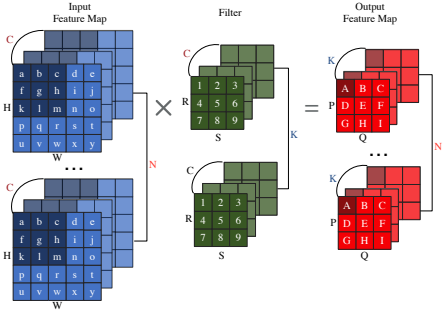
```
for m in 0..M
 for k in 0..K
  for n in 0..N
   C[m,n] += A[m,k] * B[k,n]
```



	InP	OutP	ROW
Input reuse (B)	Poor	Excellent	Poor
Output reuse (C)	Excellent	Poor	Good
Index intersection	Inefficient	Efficient	Efficient
Psum granularity	Scalar	Matrix	Vector

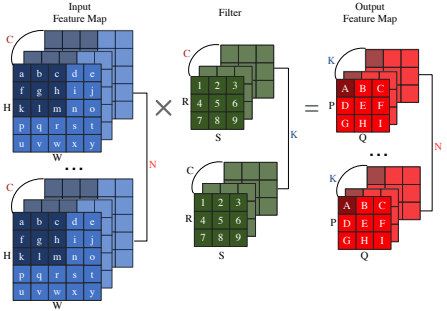
Direct Convolution

Direct Convolution



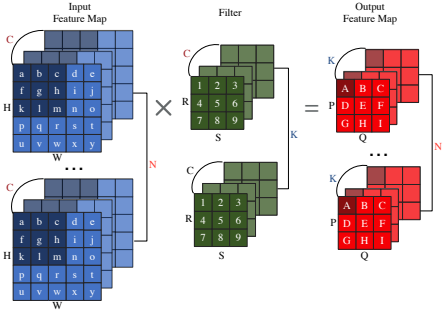

```
1       for (n=0; n<N; n++) {
2       for (k=0; k<K; k++) {
3       for (p=0; p<P; p++) {
4       for (q=0; q<Q; q++) {
5           OA[n][k][p][q]= 0;
6           for (r=0; r<R; r++) {
7           for (s=0; s<S; s++) {
8           for (c=0; c<C; c++) {
9               h = p * stride - pad + r;
10              w = q * stride - pad + s;
11              OA[n][k][p][q] += IA[n][c][h][w] * W[k][c][r][s];
12      } } } } } } }
```

Direct Convolution: Loop Ordering



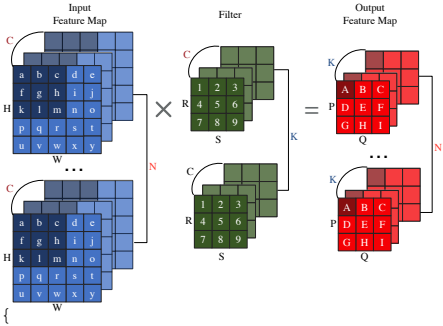

```
1     for (n=0; n<N; n++) {
2     for (r=0; r<R; r++) {
3     for (s=0; s<S; s++) {
4     for (c=0; c<C; c++) {
5     for (k=0; k<K; k++) {
6         float curr_w = W[r][s][c][k];
7         for (p=0; p<P; p++) {
8         for (q=0; q<Q; q++) {
9             h = p * stride - pad + r;
10            w = q * stride - pad + s;
11            OA[n][k][p][q] += IA[n][c][h][w] * curr_w;
12    } } } } } } }
```

Direct Convolution: Loop Ordering + Unrolling




```
1       for (n=0; n<N; n++) {
2       for (r=0; r<R; r++) {
3       for (s=0; s<S; s++) {
4           spatial_for (c=0; c<C; c++) {
5           spatial_for (k=0; k<K; k++) {
6           float curr_w = W[r][s][c][k];
7           for (p=0; p<P; p++) {
8           for (q=0; q<Q; q++) {
9               h = p * stride - pad + r;
10              w = q * stride - pad + s;
11              OA[n][k][p][q] += IA[n][c][h][w] * curr_w;
12      } } } } } } }
```

Direct Convolution: Loop Ordering + Unrolling + Tiling




```
1       for (n=0; n<N; n++) {
2       for (r=0; r<R; r++) {
3       for (s=0; s<S; s++) {
4       for (c_t=0; c_t<C/16; c_t++) {
5       for (k_t=0; k_t<K/64; k_t++) {
6       spatial_for (c_s=0; c_s<16; c_s++) {
7       spatial_for (k_s=0; k_s<64; k_s++) {
8           int curr_c = c_t * 16 + c_s;
9           int curr_k = k_t * 64 + k_s;
10          float curr_w = W[r][s][curr_c][curr_k];
11          for (p=0; p<P; p++) for (q=0; q<Q; q++) {
12              h = p * stride - pad + r; w = q * stride - pad + s;
13              OA[n][curr_k][p][q] += IA[n][curr_c][h][w] * curr_w;
14      } } } } } }
```

Dataflow Optimization

Systolic Array

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \times \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & b_{34} \\ b_{41} & b_{42} & b_{43} & b_{44} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{bmatrix}$$