Storage Requirement Estimation for Data Intensive Applications with Partially Fixed Execution Ordering

Per Gunnar Kjeldsberg
Norwegian University of Science and Technology
Trondheim, NORWAY

Francky Catthoor
IMEC, Leuven, BELGIUM
Also at EE. Dept. of Kath. Univ. Leuven

Einar J. Aas
Norwegian University of Science and Technology
Trondheim, NORWAY

In this paper, we propose a novel storage requirement estimation methodology for use in the early system design phases when the data transfer ordering is only partly fixed. Using a representative application demonstrator, we show how our technique can effectively guide the designer to achieve a transformed specification with low storage requirement.

Motivation and Context

For data dominated HW/SW systems:

- Data transfer and storage determine cost and performance parameters.
- Must be main focus of the designer to achieve cost-optimized end product [Catthoor98].

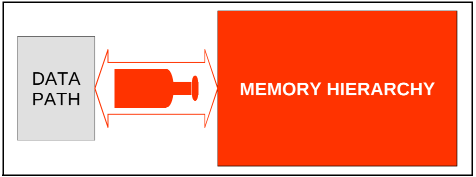


Figure 1: Data dominated embedded system

- At system level no detailed storage requirement information is available.
- Estimation techniques are essential.
- High-level description characterized by large multi-dimensional loop nests and arrays.

```
for (y_s=0; y_s<=31; y_s++) {
  for (x_s=0; x_s<=31; x_s++) {
    for (y_p=0; y_p<=15; y_p++) {
      for (x_p=0; x_p<=15; x_p++) {
        if ((x_p == 0)&(y_p == 0)) sad[y_s][x_s][y_p][x_p]=
                              f(curr[y_p][x_p], prev[y_s+y_p][x_s+x_p]);
        else if ((x_p == 0)&(y_p != 0)) sad[y_s][x_s][y_p][x_p]=
                              g(sad[y_s][x_s][y_p-1][15], curr[y_p][x_p],
                                                 prev[y_s+y_p][x_s+x_p]);
        else sad[y_s][x_s][y_p][x_p]= g(sad[y_s][x_s][y_p][x_p-1],
                               curr[y_p][x_p], prev[y_s+y_p][x_s+x_p]);
} } } }
```

Figure 2: Code example (MPEG-4 motion estimation kernel)

- Accurate estimates must take in-place mapping possibilities into account.
- Mainly decided by the ordering of the loops surrounding the arrays.
- Design decisions gradually fix this execution ordering.
- Estimates of upper and lower bounds on storage requirement needed at each step, given the partially fixed execution ordering.
- Previous work either assumes a fully fixed ordering, e.g. [Zhao99], or does not take it into account at all [Balasa95].

Estimation Methodology

Generate data-flow graph reflecting data dependencies in the application code

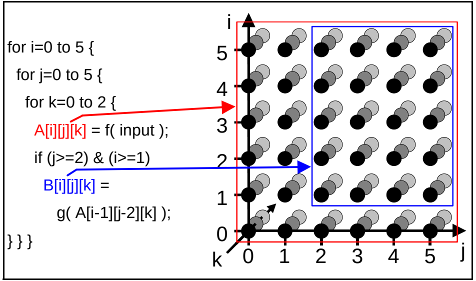
↓

Estimate upper and lower bounds on dependency sizes per signal based on partly fixed execution ordering

↓

Traverse the data-flow graph to find the total size of simultaneously alive dependencies
=
Bounds on the application's storage requirement

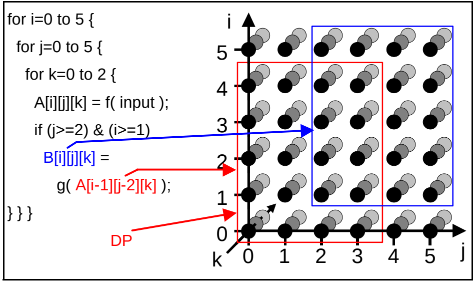
- Figure 3 shows a simple code example.
- Array elements are produced at specific locations in the iteration space.



```
for i=0 to 5 {
  for j=0 to 5 {
    for k=0 to 2 {
      A[i][j][k] = f( input );
      if (j>=2) & (i>=1)
        B[i][j][k] =
          g( A[i-1][j-2][k] );
} } }
```

Figure 3: Iteration space and production of array elements

Dependency Part (DP):
Array elements produced by one instruction and read by another instruction, see Figure 4.

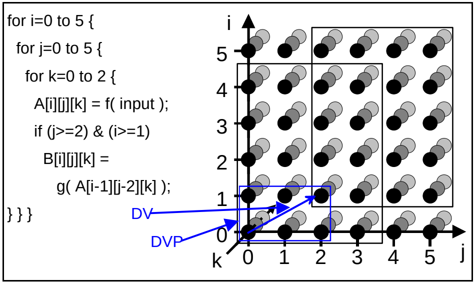


```
for i=0 to 5 {
  for j=0 to 5 {
    for k=0 to 2 {
      A[i][j][k] = f( input );
      if (j>=2) & (i>=1)
        B[i][j][k] =
          g( A[i-1][j-2][k] );
} } }
```

Figure 4: Dependency Part

Dependency Vector (DV):
Vector in iteration space between two depending array elements. There is a DV between (i,j,k)-points (0,0,0) and (1,2,0), see Figure 5.

Dependency Vector Polytope (DVP):
The polytope spanned by the DV after intersection with the DP, see Figure 5.

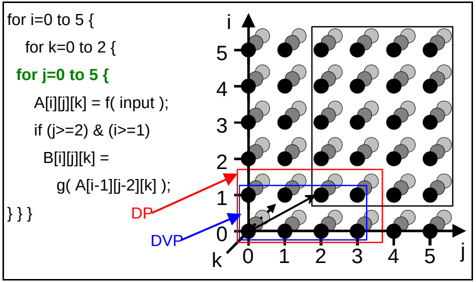


```
for i=0 to 5 {
  for j=0 to 5 {
    for k=0 to 2 {
      A[i][j][k] = f( input );
      if (j>=2) & (i>=1)
        B[i][j][k] =
          g( A[i-1][j-2][k] );
} } }
```

Figure 5: Dependency Vector and Dependency Vector Polytope

Spanning/Nonspanning Dimensions (SD/ND):
The iteration space dimensions that are/are not a part of the DVP. In Figure 5: SD={*i*,*j*}, ND={*k*}.

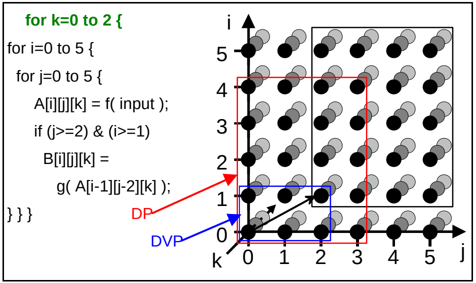
Estimate with no execution ordering fixed:
Upper Bound (UB) = Size (DP) - Overlap = 36
Lower Bound (LB) = Size (DVP) - Overlap = 5



```
for i=0 to 5 {
  for k=0 to 2 {
    for j=0 to 5 {
      A[i][j][k] = f( input );
      if (j>=2) & (i>=1)
        B[i][j][k] =
          g( A[i-1][j-2][k] );
} } }
```

Figure 6: Spanning Dimension j fixed innermost

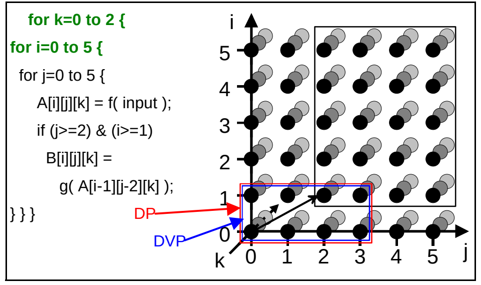
Estimate with SD *j* innermost:
DP reduced → UB=18. DVP extended → LB=6. See Figure 6.



```
for k=0 to 2 {
for i=0 to 5 {
  for j=0 to 5 {
    A[i][j][k] = f( input );
    if (j>=2) & (i>=1)
      B[i][j][k] =
        g( A[i-1][j-2][k] );
} } }
```

Figure 7: Nonspanning Dimension k fixed outermost

Estimate with ND *k* outermost:
DP reduced → UB=12. DVP unchanged → LB=5. See Figure 7.



```
  for k=0 to 2 {
for i=0 to 5 {
  for j=0 to 5 {
    A[i][j][k] = f( input );
    if (j>=2) & (i>=1)
      B[i][j][k] =
        g( A[i-1][j-2][k] );
} } }
```

Figure 8: Spanning Dimension i fixed second outermost

Estimate with SD *i* second outermost:
DP reduced → UB=6. DVP extended → LB=6. See Figure 8.

MPEG-4 Motion Estimation Kernel

- Methodology employed during the early loop transformation design phase of an MPEG-4 motion estimation kernel, see Figure 2.
- Focus on the two-dimensional curr[y_p][x_p] and four-dimensional sad[y_s][x_s][y_p][x_p] arrays.
- The curr array has smallest storage requirement with y_p outermost.
- Estimates showed large penalty on sad array and total storage requirement, see Figure 9.
- Better ordering with y_s outermost was found.

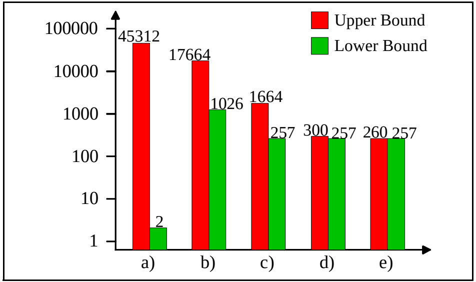


Figure 9: Total storage requirement a) No ordering, b) y_p outermost, c) y_s outermost, d) x_s second outermost, e) y_p third outermost and x_p fourth outermost

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