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fakultät für informatik
informatik 12

Optimizations

- Compilation for Embedded Processors -

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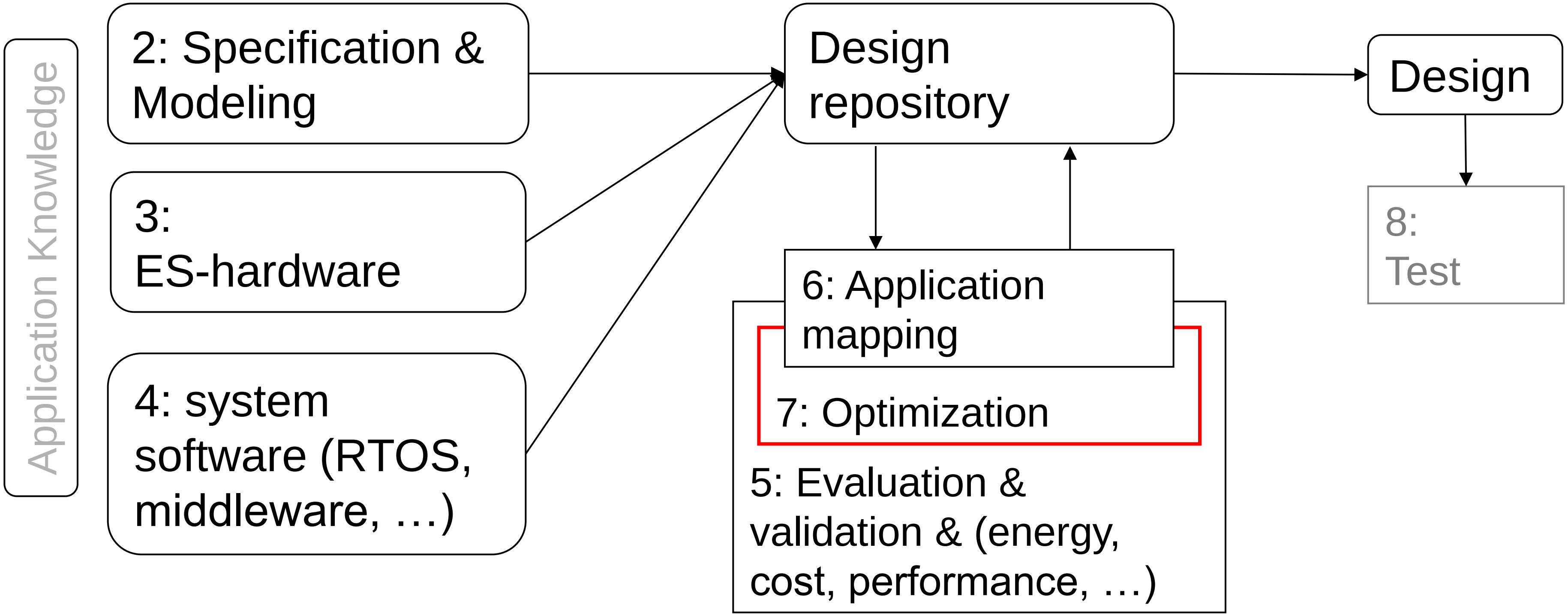
Structure of this course



Numbers denote sequence of chapters

Task-level concurrency management

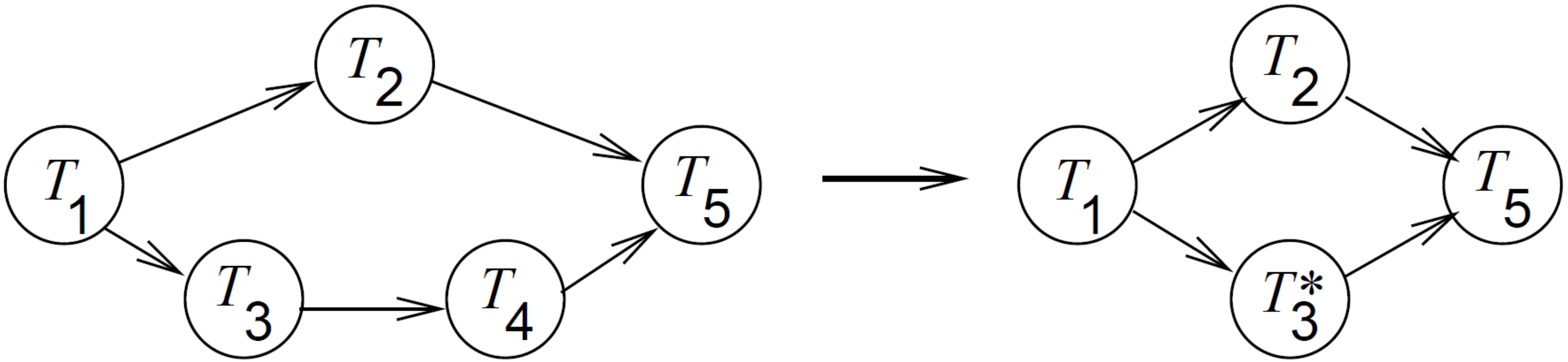
Book section 7.1

Granularity: size of tasks (e.g. in instructions)

Readable specifications and efficient implementations can possibly require different task structures.

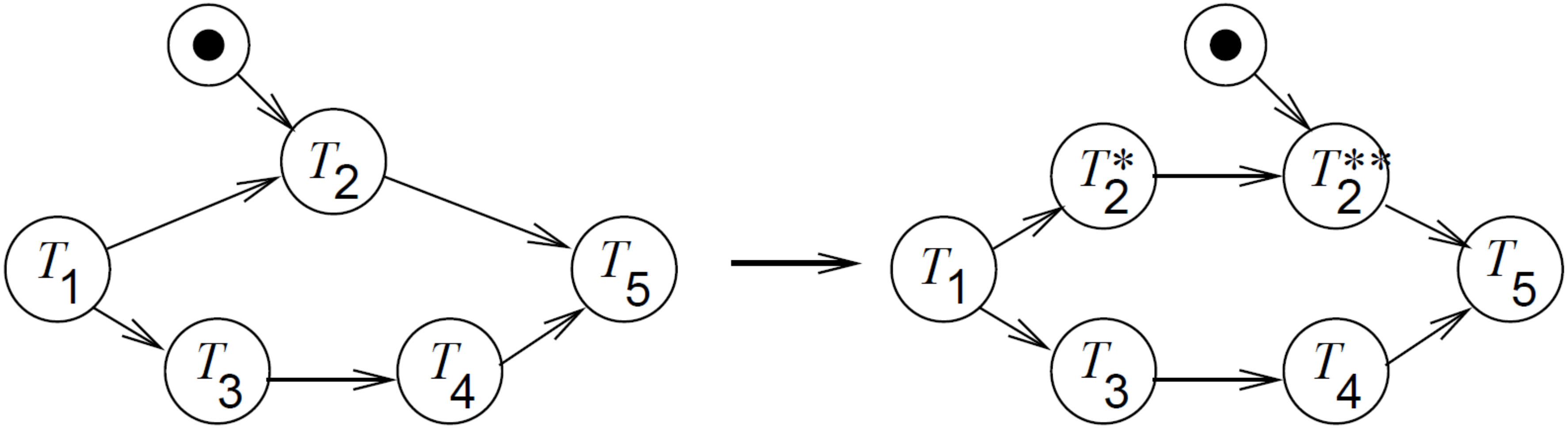
☞ Granularity changes

Merging of tasks



Reduced overhead of context switches,
More global optimization of machine code,
Reduced overhead for inter-process/task communication.

Splitting of tasks



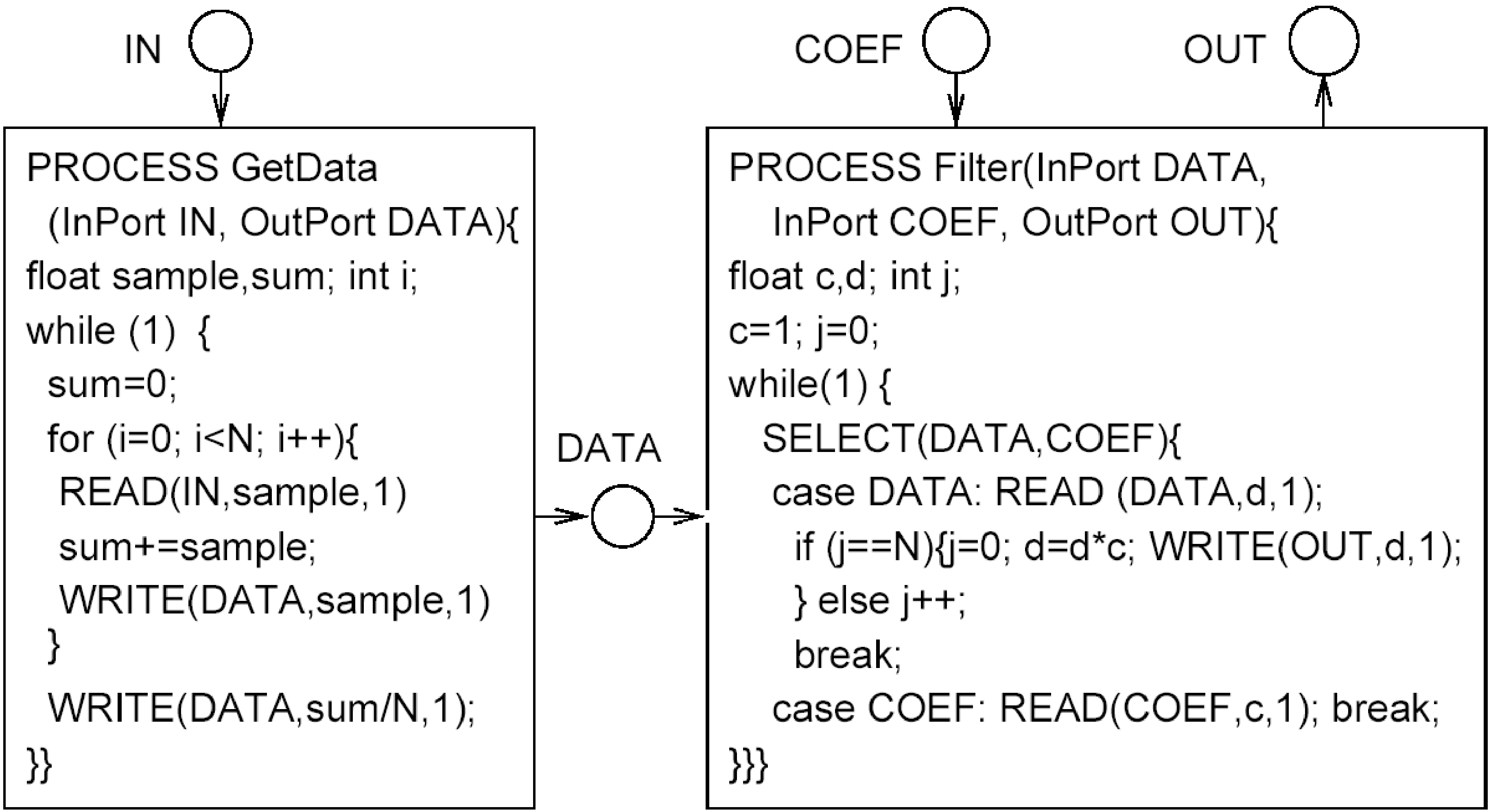
No blocking of resources while waiting for input,
more flexibility for scheduling, possibly improved result.

Merging and splitting of tasks

The most appropriate task graph granularity depends upon the context ☞ merging and splitting may be required.

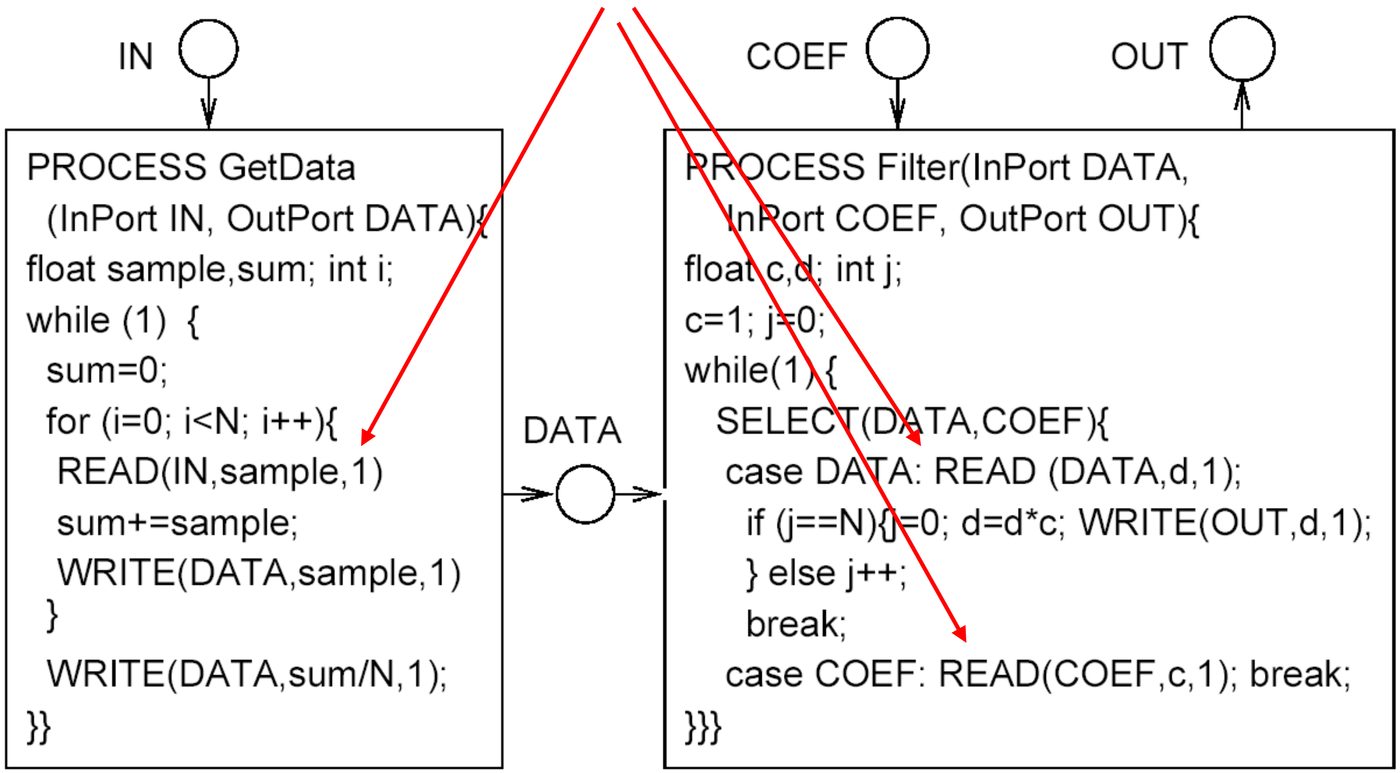
Merging and splitting of tasks should be done automatically, depending upon the context.

Automated rewriting of the task system - Example -



Attributes of a system that needs rewriting

Tasks blocking after they have already started running



Work by Cortadella et al.

1. Transform each of the tasks into a Petri net,
2. Generate one global Petri net from the nets of the tasks,
3. Partition global net into “sequences of transitions”
4. Generate one task from each such sequence

Mature, commercial approach not yet available

Result, as published by Cortadella

Reads only at the beginning

Initialization task

IN

OUT

```
Init(){
  sum=0;i=0;c=1;j=0;
}
```

```
Tin(){
  READ(IN,sample,1);
  sum+=sample; i++;
  DATA=sample; d=DATA;
  if (j==N) {j=0; d=d*c; WRITE(OUT,d,1);
              }else j++;
L0: if (i<N) return;
  DATA=sum/N; d=DATA;
  if (j==N) {j=0; d=d*c; WRITE(OUT,d,1);
      }else j++;
  sum=0; i=0; goto L0
}
```

Never true

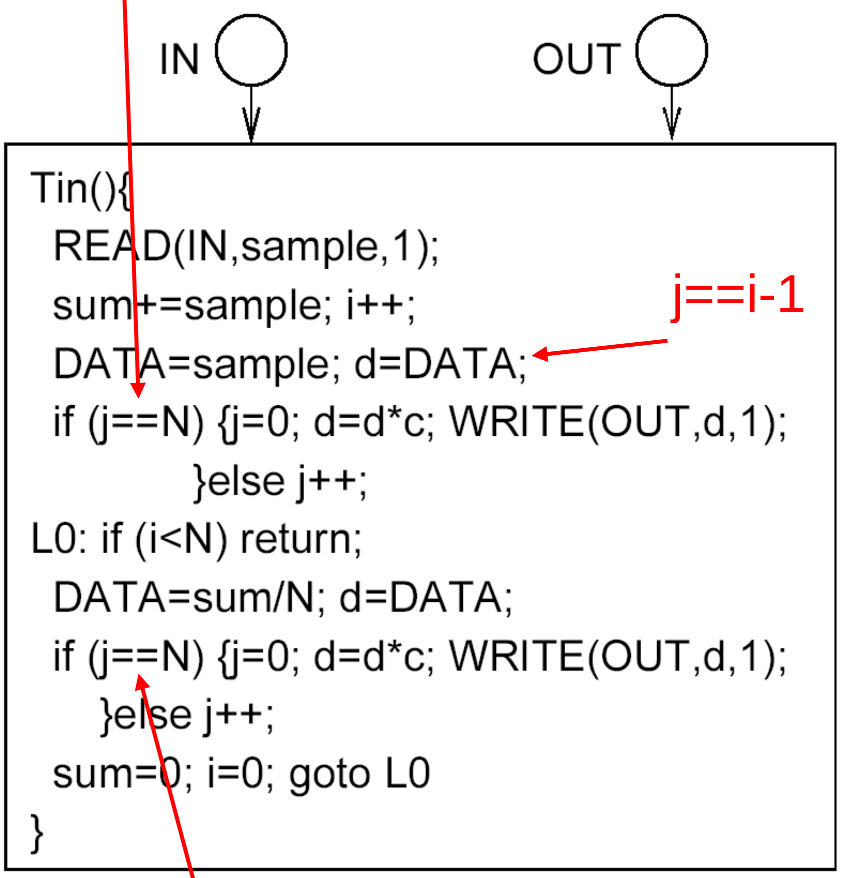
COEF

```
Tcoef(){
  READ(COEF,c,1);
}
```

Always true

Optimized version of Tin

Never true



j==i-1

j ☞ i

```
Tin () {
READ (IN, sample, 1);
sum += sample; i++;
DATA = sample; d = DATA;
L0: if (i < N) return;
DATA = sum/N; d = DATA;
d = d*c; WRITE(OUT,d,1);
sum = 0; i = 0;
return;
}
```

Always true

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High-level software transformations

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High-level optimizations

Book section 7.2

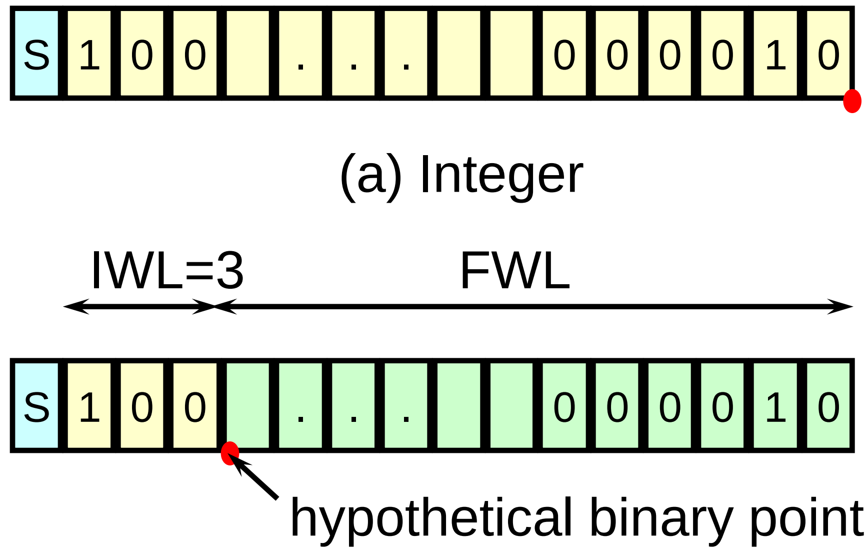
- Floating-point to fixed point conversion
- Simple loop transformations
- Loop tiling/blocking
- Loop (nest) splitting
- Array folding

Fixed-Point Data Format

- Floating-Point vs. Fixed-Point

- Integer vs. Fixed-Point

- *exponent*, mantissa
- Floating-Point
  - automatic computation and update of each exponent at run-time
- Fixed-Point
  - implicit exponent
  - determined off-line



(a) Integer

(b) Fixed-Point

© Ki-Il Kum, et al

Floating-point to fixed point conversion

Pros:

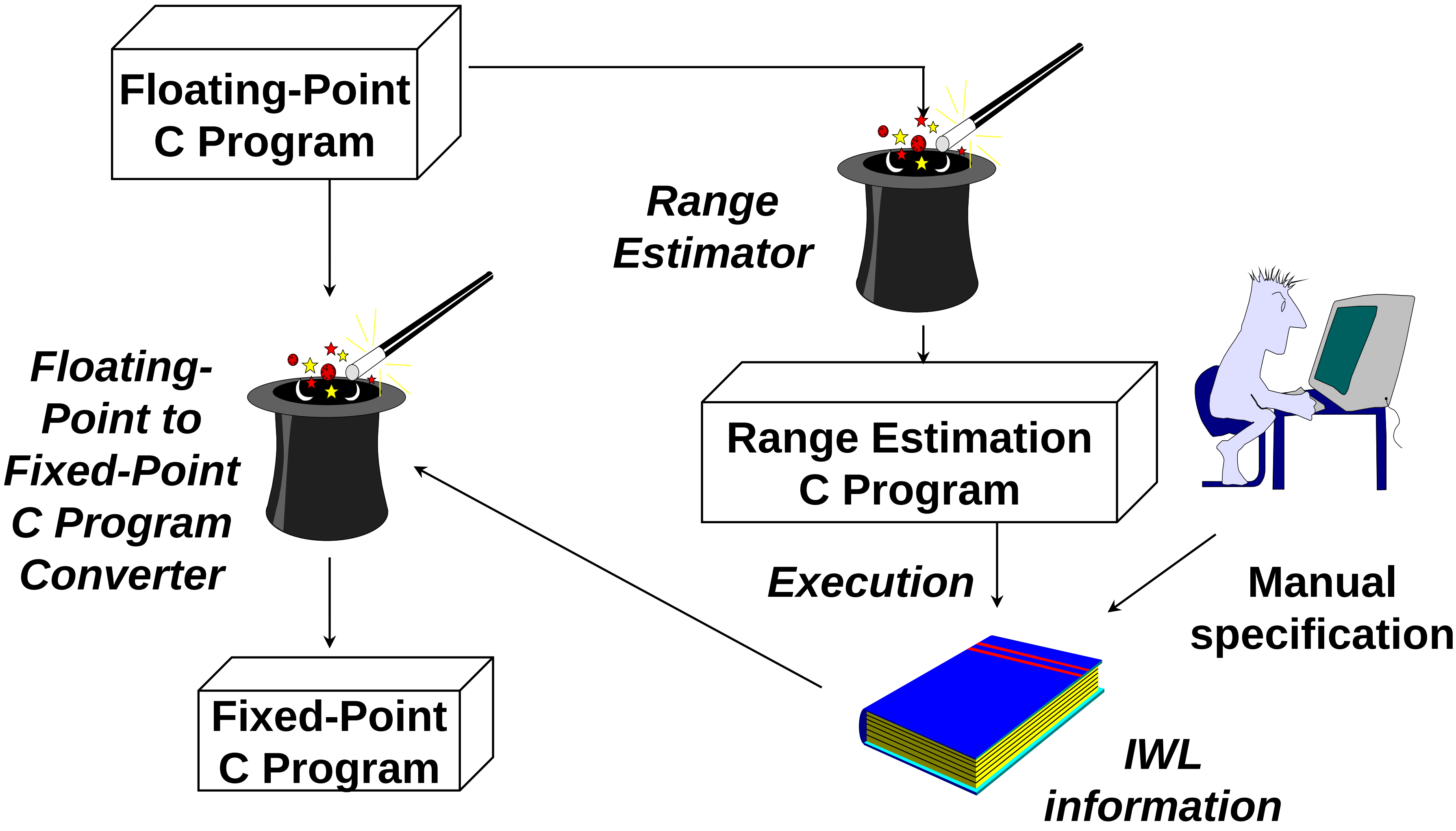
- Lower cost
- Faster
- Lower power consumption
- Sufficient SQNR, *if properly scaled*
- Suitable for portable applications

Cons:

- Decreased dynamic range
- Finite word-length effect, *unless properly scaled*
  - Overflow and excessive quantization noise
- Extra programming effort

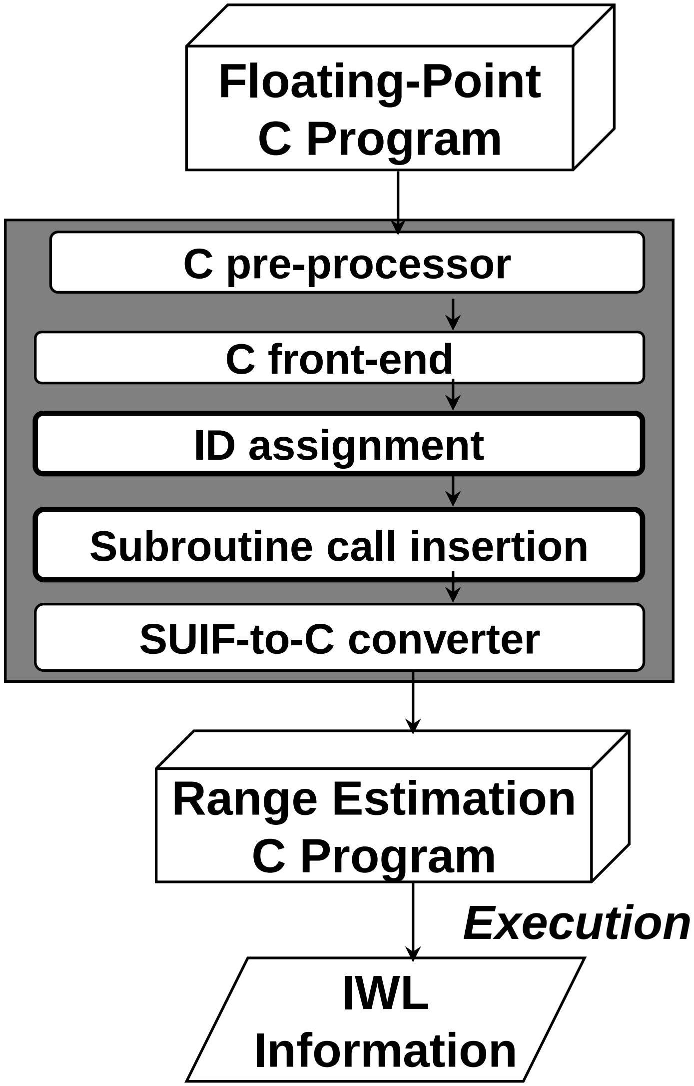
© *Ki-Il Kum, et al. (*Seoul National University)*:* A Floating-point To Fixed-point C Converter For Fixed-point Digital Signal Processors, 2nd SUIF Workshop, 1996

Development Procedure



© Ki-Il Kum, et al

Range Estimator



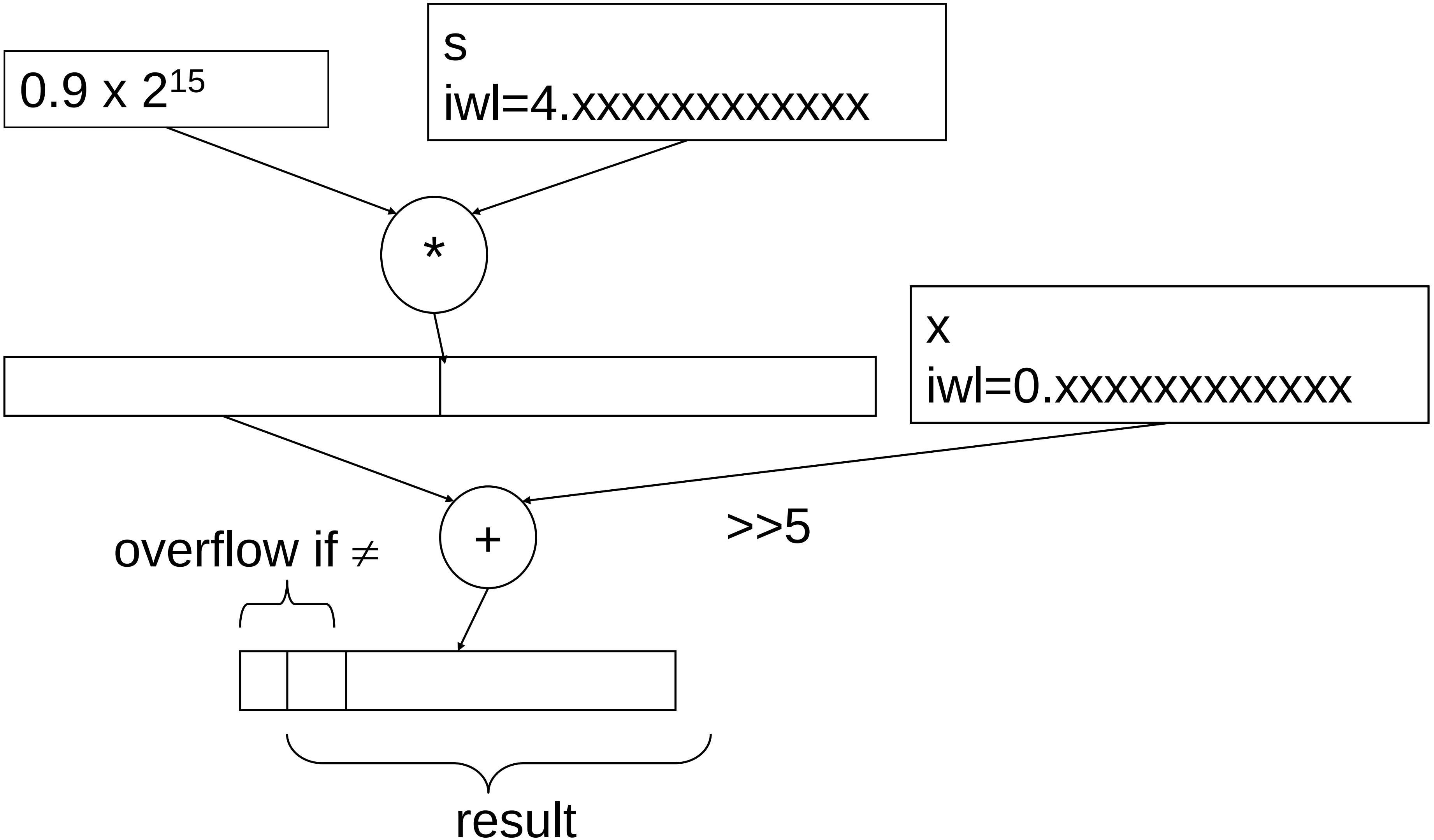
Range Estimation C Program

```
float iir1(float x)
{
    static float s = 0;
    float y;

    y = 0.9 * s + x;
    range(y, 0);
    s = y;
    range(s, 1);

    return y;
}
```

Operations in fixed point program



Floating-Point to Fixed-Point Program Converter

Fixed-Point C Program

```
int iir1(int x)
{
 static int s = 0;
 int y;
 y=sll(mulh(29491,s)+ (x>> 5),1);
 s = y;
 return y;
}
```

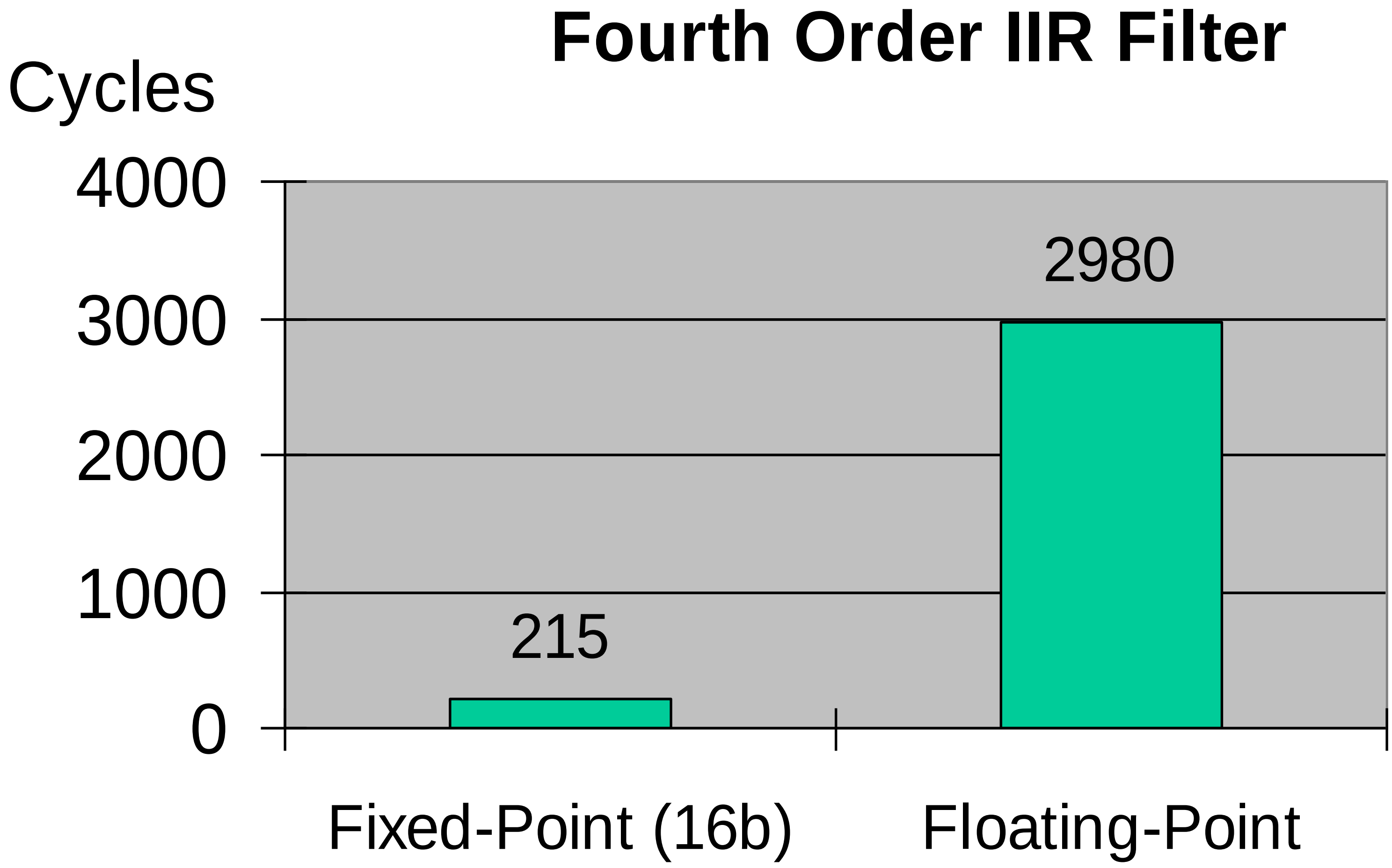
mulh

- to access the upper half of the multiplied result
- target dependent implementation

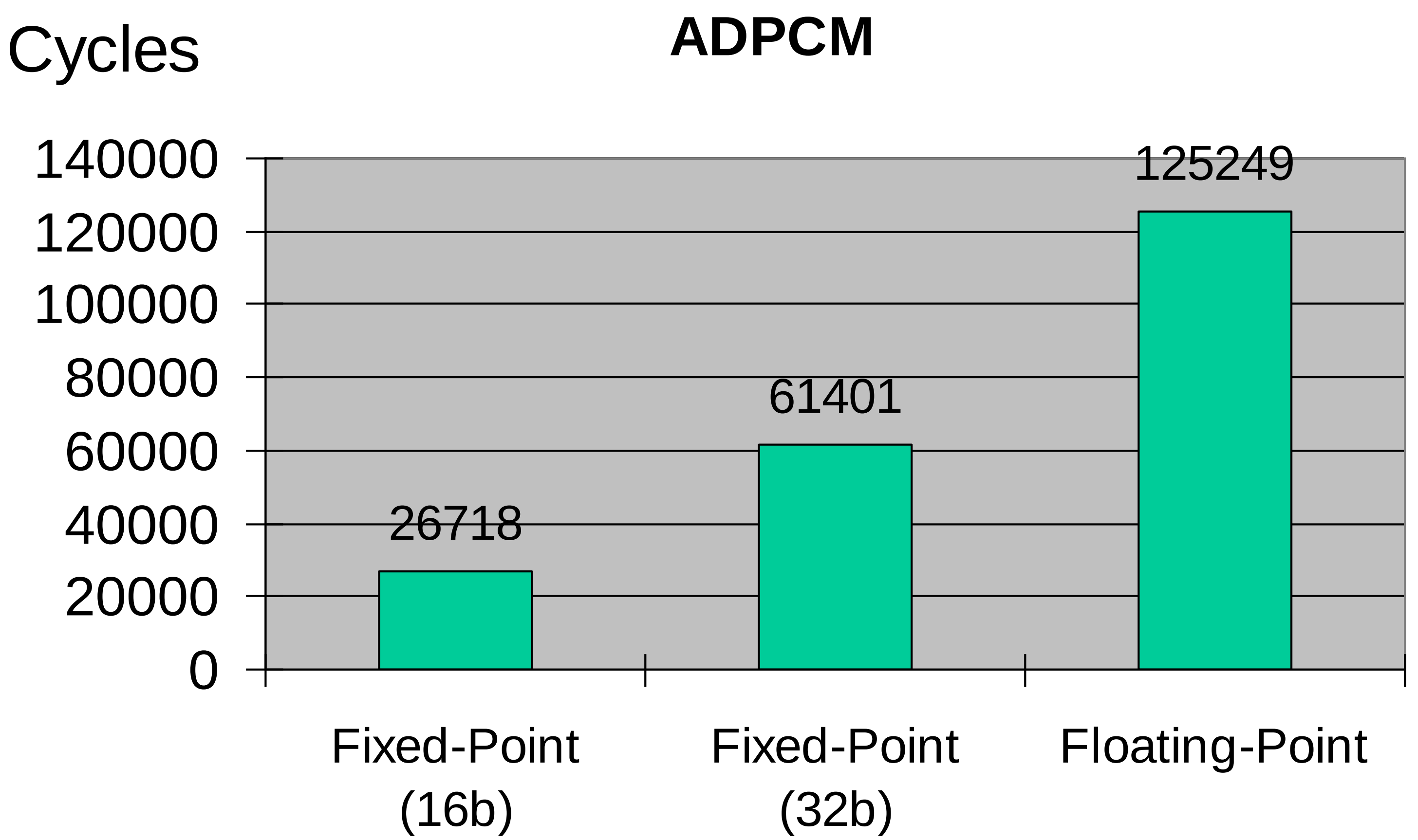
sll

- to remove 2nd sign bit
- opt. overflow check

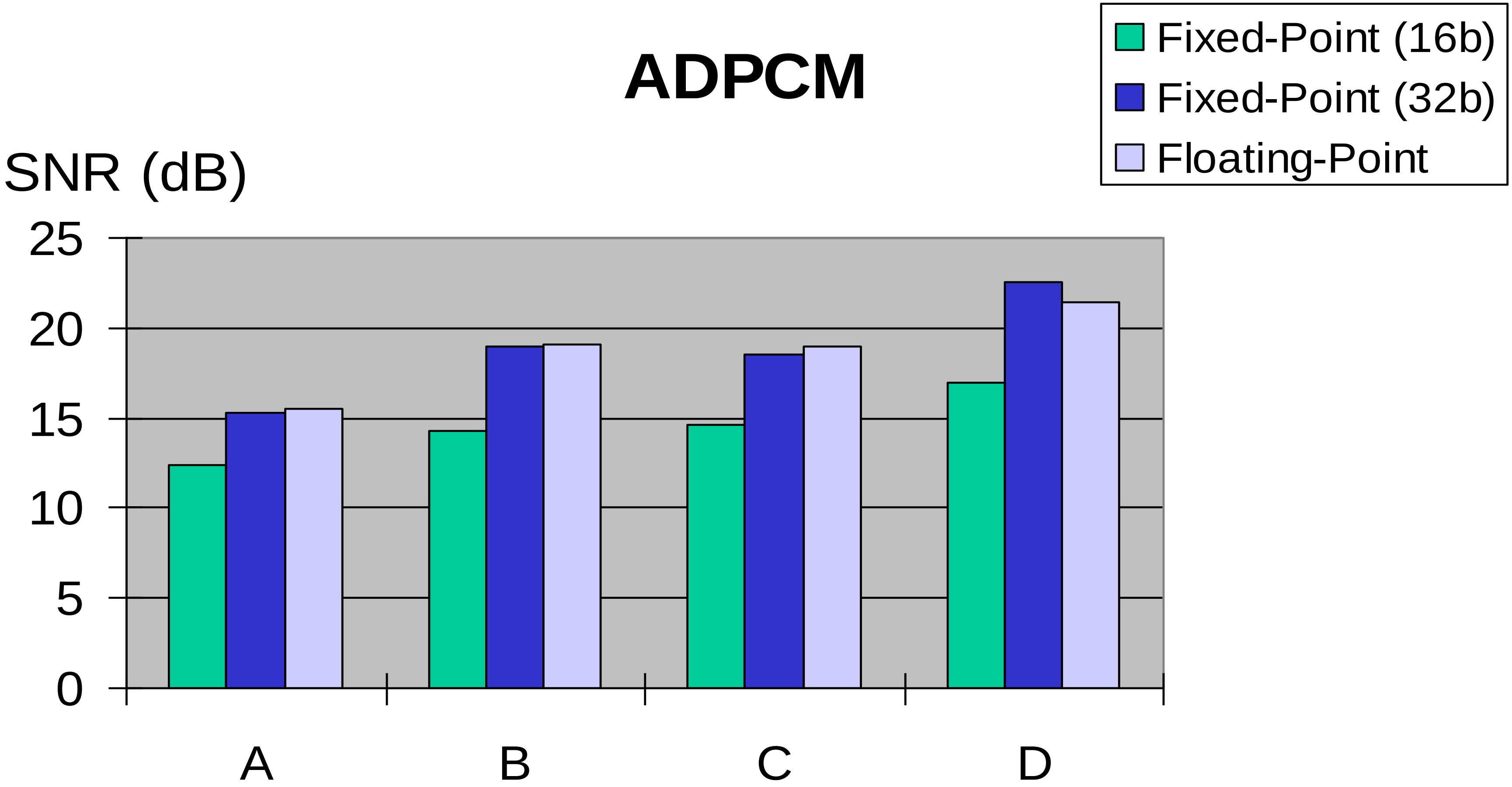
Performance Comparison - Machine Cycles -



Performance Comparison - Machine Cycles -



Performance Comparison - SNR -



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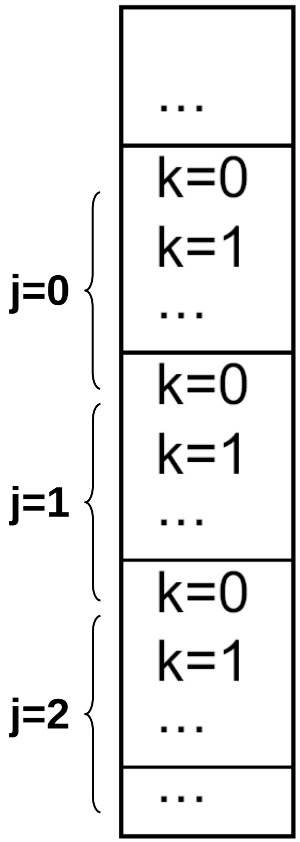
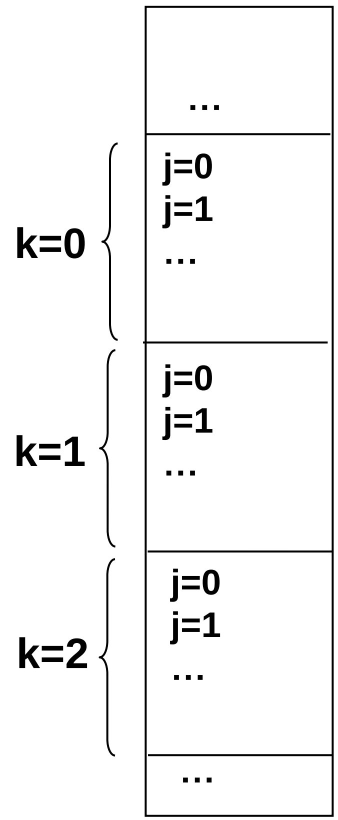
Impact of memory allocation on efficiency

Array p[j][k]

Row major order (C)



Column major order (FORTRAN)



Best performance of innermost loop corresponds to rightmost array index

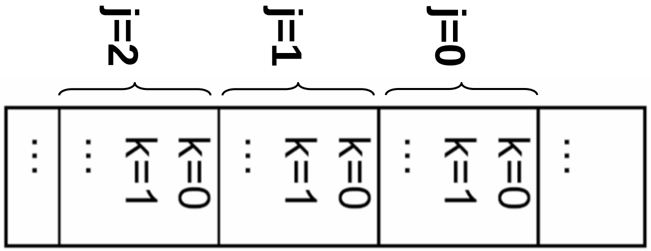
Two loops, assuming row major order (C):

```
for (k=0; k<=m; k++)
  for (j=0; j<=n; j++) )
    p[j][k] = ...
```

```
for (j=0; j<=n; j++)
  for (k=0; k<=m; k++)
   p[j][k] = ...
```

Same behavior for homogeneous memory access, but:

For row major order



↑ Poor cache behavior   Good cache behavior ↑

☞ memory architecture dependent optimization

☞ Program transformation “Loop interchange”

☞ Improved locality

```
Example:
…#define iter 400000
int a[20][20][20];
void computeijk() {int i,j,k;
  for (i = 0; i < 20; i++) {
      for (j = 0; j < 20; j++) {
            for (k = 0; k < 20; k++) {
                  a[i][j][k] += a[i][j][k];}}}}
void computeikj() {int i,j,k;
  for (i = 0; i < 20; i++) {
      for (j = 0; j < 20; j++) {
            for (k = 0; k < 20; k++) {
                  a[i][k][j] += a[i][k][j] ;}}}}…
start=time(&start);for(z=0;z<iter;z++)computeijk();
  end=time(&end);
  printf("ijk=%16.9f\n",1.0*difftime(end,start));
```

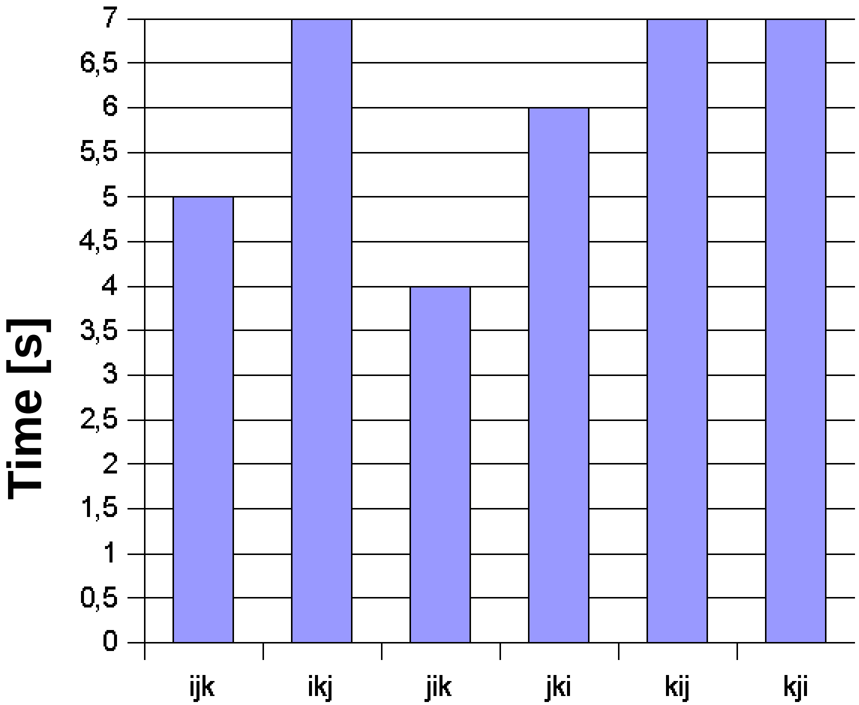
(SUIF interchanges array indexes instead of loops)

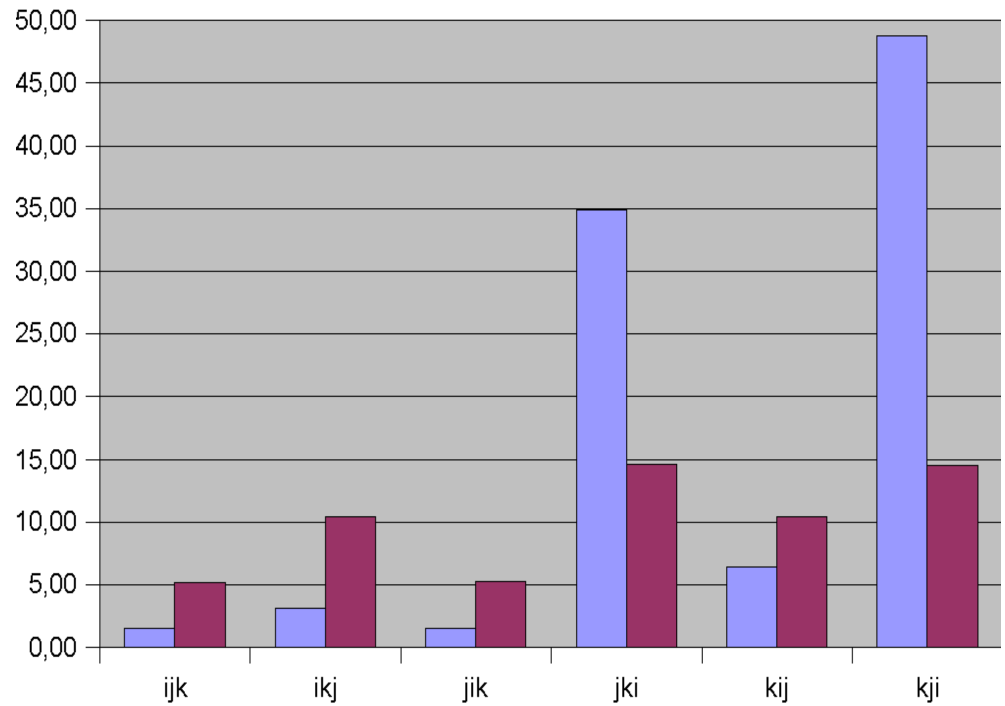
Results: strong influence of the memory architecture

Loop structure: i j k

Dramatic impact of locality

Processor	Ti C6xx	Sun SPARC	Intel Pentium
reduction to [%]	~ 57%	35%	3.2 %





Not always the same impact ..

[Till Buchwald, Diploma thesis, Univ. Dortmund, Informatik 12, 12/2004]

Transformations
"Loop fusion" (merging), "loop fission"

```
for(j=0; j<=n; j++)
  p[j]= ... ;
for (j=0; j<=n; j++) ,
  p[j]= p[j] + ...
```

Loops small enough to allow zero overhead Loops

```
for (j=0; j<=n; j++)
  {p[j]= ... ;
  p[j]= p[j] + ...}
```

Better locality for access to p.
Better chances for parallel execution.

Which of the two versions is best?
Architecture-aware compiler should select best version.

Example: simple loops

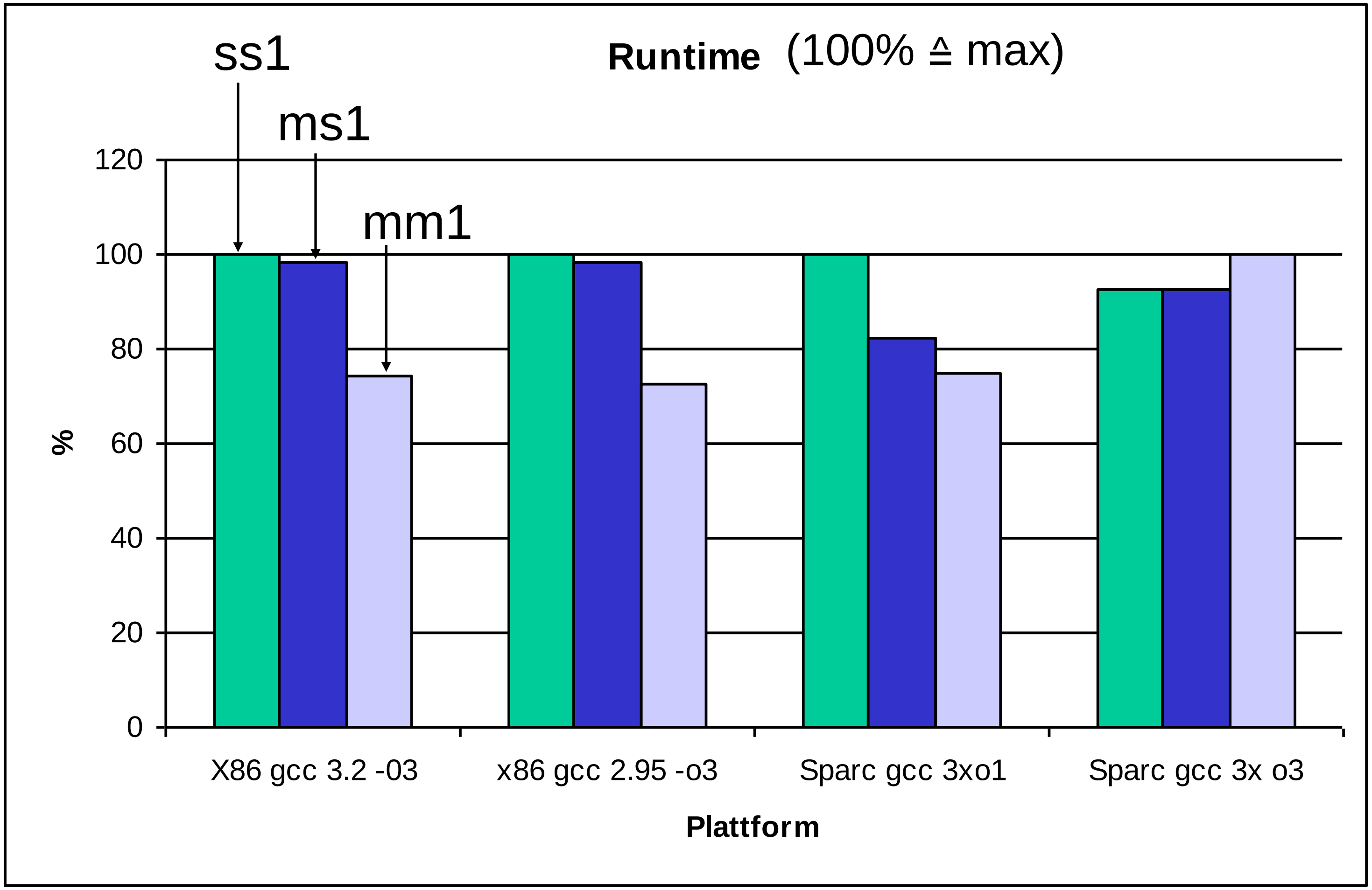
```
#define size 30
#define iter 40000
int a[size][size];
float b[size][size];
```

```
void ss1() {int i,j;
 for (i=0;i<size;i++){
  for (j=0;j<size;j++){
   a[i][j]+= 17;}}
 for(i=0;i<size;i++){
  for (j=0;j<size;j++){
   b[i][j]-=13;}}}
```

```
void ms1() {int i,j;
 for (i=0;i< size;i++){
  for (j=0;j<size;j++){
   a[i][j]+=17;     }
  for (j=0;j<size;j++){
   b[i][j]-=13;  }}}
```

```
void mm1() {int i,j;
 for(i=0;i<size;i++){
  for(j=0;j<size;j++){
   a[i][j] += 17;
   b[i][j] -= 13;}}}
```

Results: simple loops



☞ Merged loops superior; except Sparc with –o3

Loop unrolling

```
for (j=0; j<=n; j++)
p[j]= ... ;
```

```
for (j=0; j<=n; j+=2)
    {p[j]= ... ; p[j+1]= ...}
```

factor = 2

Better locality for access to p.

Less branches per execution of the loop. More opportunities for optimizations.

Tradeoff between code size and improvement.

Extreme case: completely unrolled loop (no branch).

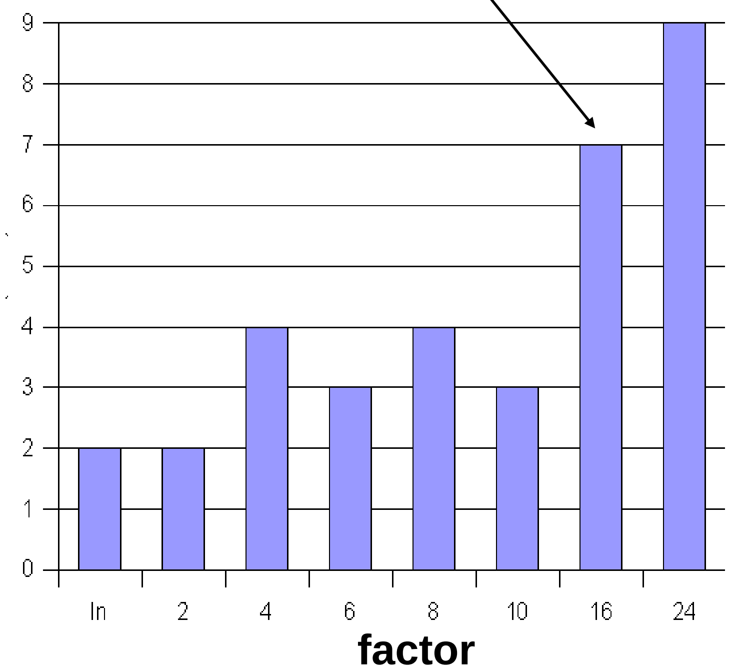
Example: matrixmult

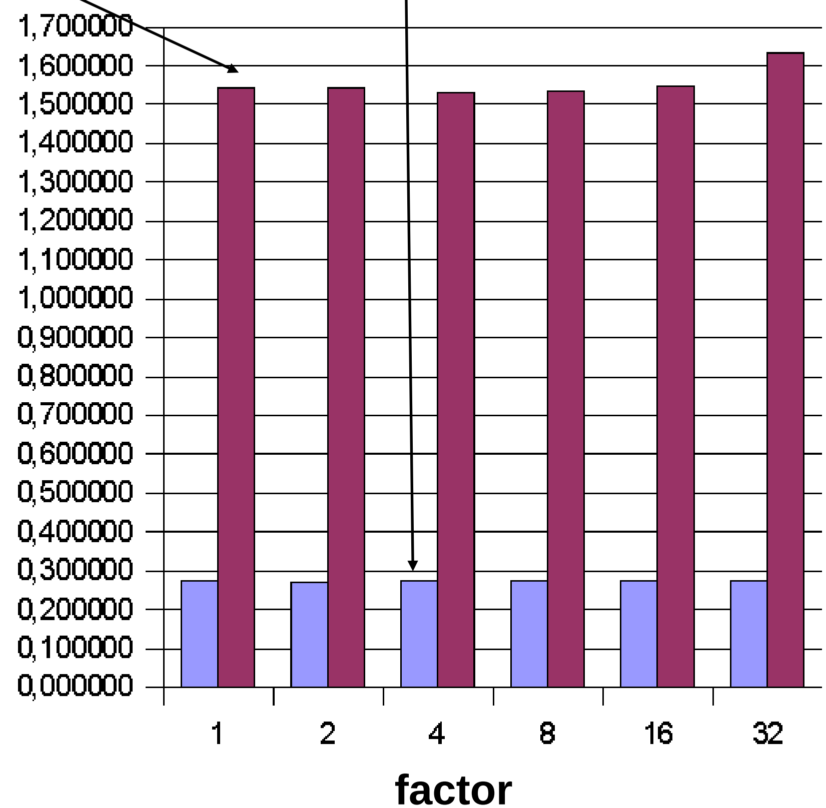
```
#define s 30
#define iter 4000
int
a[s][s],b[s][s],c[s]
[s];
void compute(){int
i,j,k;
 for(i=0;i<s;i++){
  for(j=0;j<s;j++){
   for(k=0;k<s;k++){
    c[i][k]+=
    a[i][j]*b[j][k];
}}}}
```

```
extern void compute2()
 {int i, j, k;
  for (i = 0; i < 30; i++) {
   for (j = 0; j < 30; j++)  {
    for (k = 0; k <= 28; k += 2)
     {{int *suif_tmp;
     suif_tmp = &c[i][k];
     *suif_tmp=
     *suif_tmp+a[i][j]*b[j][k];}
     {int *suif_tmp;
     suif_tmp=&c[i][k+1];
     *suif_tmp=*suif_tmp
              +a[i][j]*b[j][k+1];
  }}}}
 return;}
```

Results

Processor	Ti C6xx	Sun SPARC	Intel Pentium





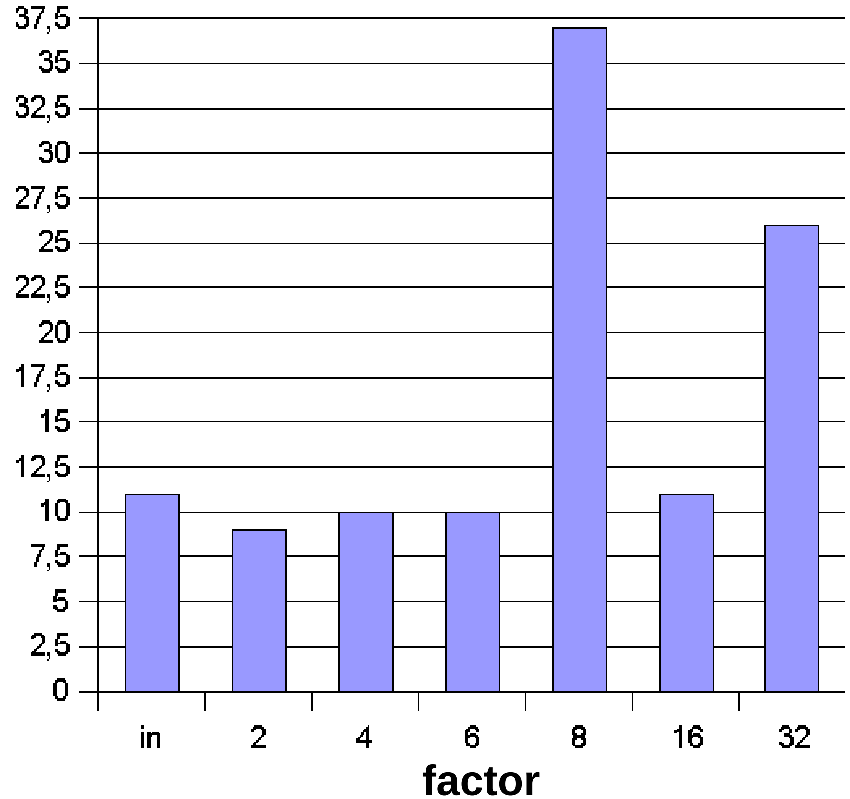
Benefits quite small; penalties may be large

[Till Buchwald, Diploma thesis, Univ. Dortmund, Informatik 12, 12/2004]

Results: benefits for loop dependences

Processor	Ti C6xx
reduction to [%]	

```
#define s 50
#define iter 150000
int a[s][s], b[s][s];
void compute() {
 int i,k;
  for (i = 0; i < s; i++) {
   for (k = 1; k < s; k++) {
    a[i][k] = b[i][k];
    b[i][k] = a[i][k-1];
}}}
```



Small benefits;

[Till Buchwald, Diploma thesis, Univ. Dortmund, Informatik 12, 12/2004]

High-level optimizations

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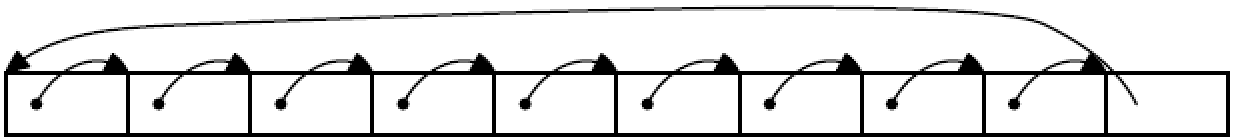
Impact of caches on execution times?

- Execution time for traversal of linked list, stored in an array, each entry comprising NPAD*8 Bytes



- Pentium P4
- 16 kB L1 data cache, 4 cycles/access
- 1 MB L2 cache, 14 cycles/access
- Main memory, 200 cycles/access

U. Drepper: *What every programmer should know about memory**, 2007, http://www.akkadia.org/drepper/cpumemory.pdf; Dank an Prof. Teubner (LS6) für Hinweis auf diese Quelle
* In Anlehnung an das Papier „David Goldberg, *What every programmer should know about floating point arithmetic, ACM Computing Surveys*, 1991 (auch für diesen Kurs benutzt).

Cycles/access as a function of the size of the list

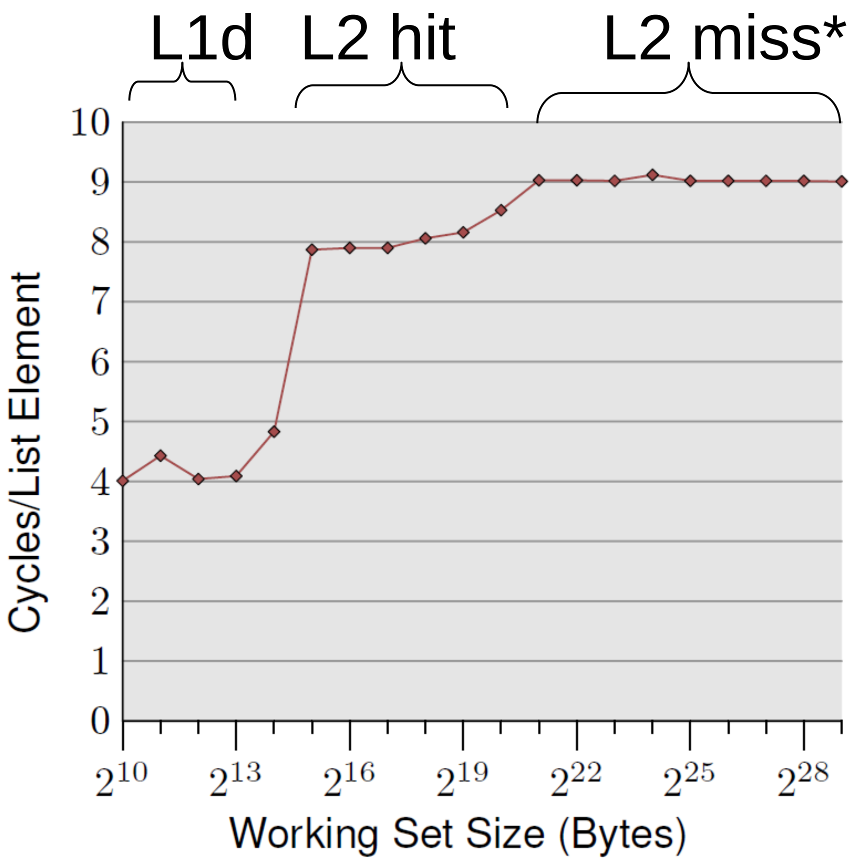
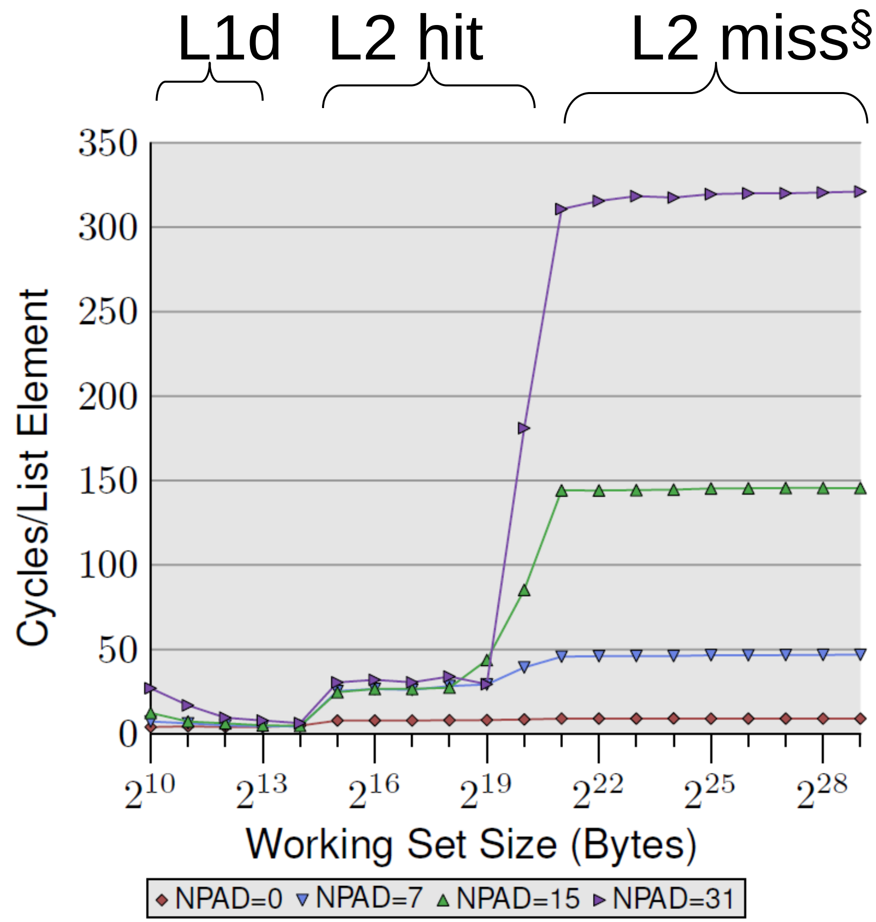


Figure 3.10: Sequential Read Access, NPAD=0

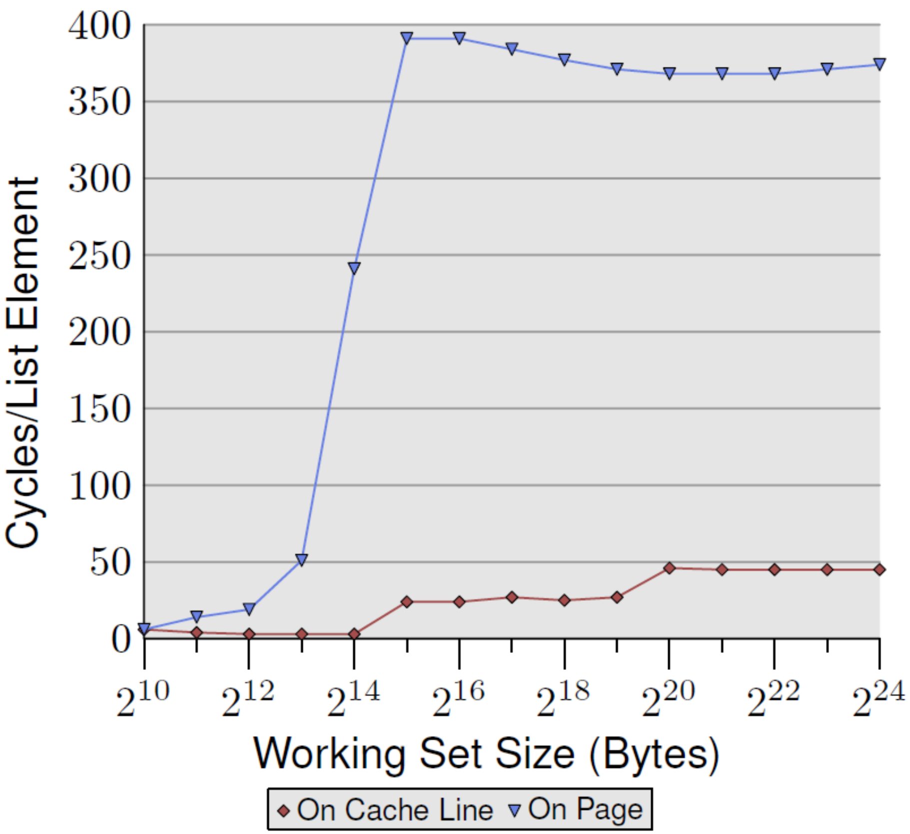


* prefetching succeeds

§ prefetching fails

Impact of TLB misses and larger caches

Elements on different pages; run time increase when exceeding the size of the TLB



Larger caches are shifting the steps to the right

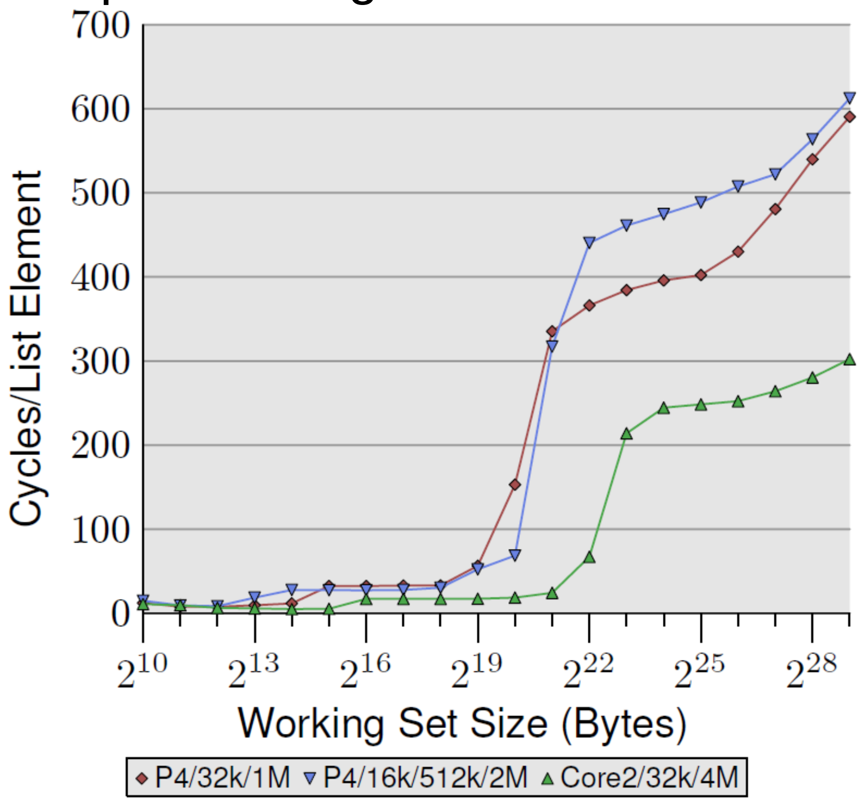
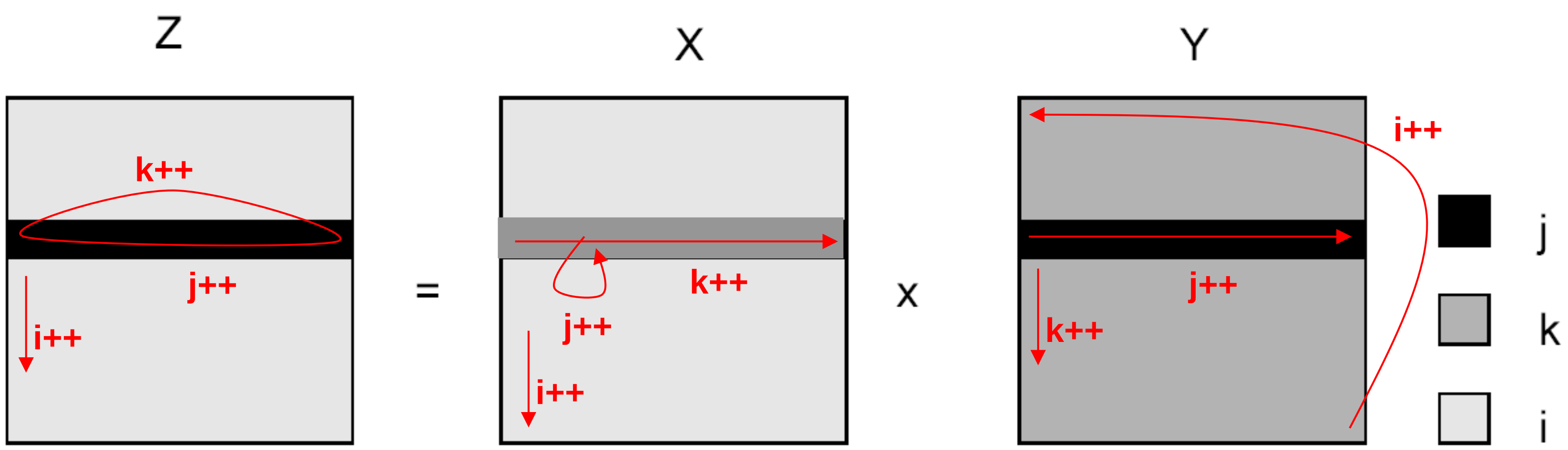


Figure 3.14: Advantage of Larger L2/L3 Caches

Program transformation
Loop tiling/loop blocking: - Original version -

```
for (i=1; i<=N; i++)
  for(k=1; k<=N; k++){
      r=X[i,k]; /* to be allocated to a register*/
      for (j=1; j<=N; j++)
            Z[i,j] += r* Y[k,j]
} % Never reusing information in the cache for Y and Z if N
  is large or cache is small (2 N³ references for Z).
```



Loop tiling/loop blocking
- tiled version -

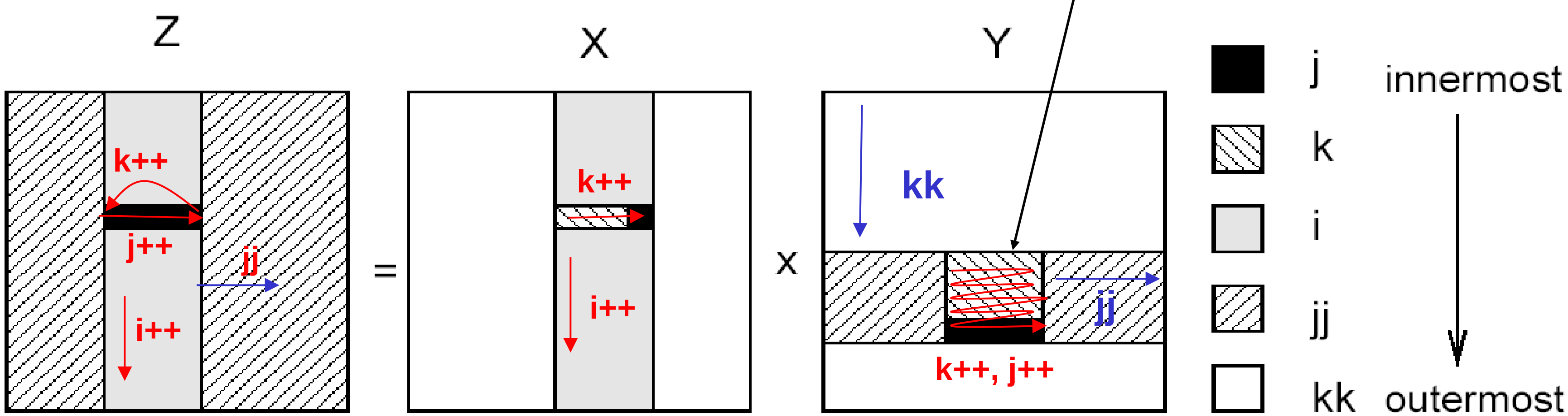
```
for (kk=1; kk<= N; kk+=B)
 for (jj=1; jj<= N; jj+=B)
  for (i=1; i<= N; i++)
   for (k=kk; k<= min(kk+B-1,N); k++){
    r=X[i][k]; /* to be allocated to a register*/
    for (j=jj; j<= min(jj+B-1, N); j++)
     Z[i][j] += r* Y[k][j]
    }
```

Reuse factor of B for Z, N for Y

$O(N^3/B)$ accesses to main memory

Compiler should select best option

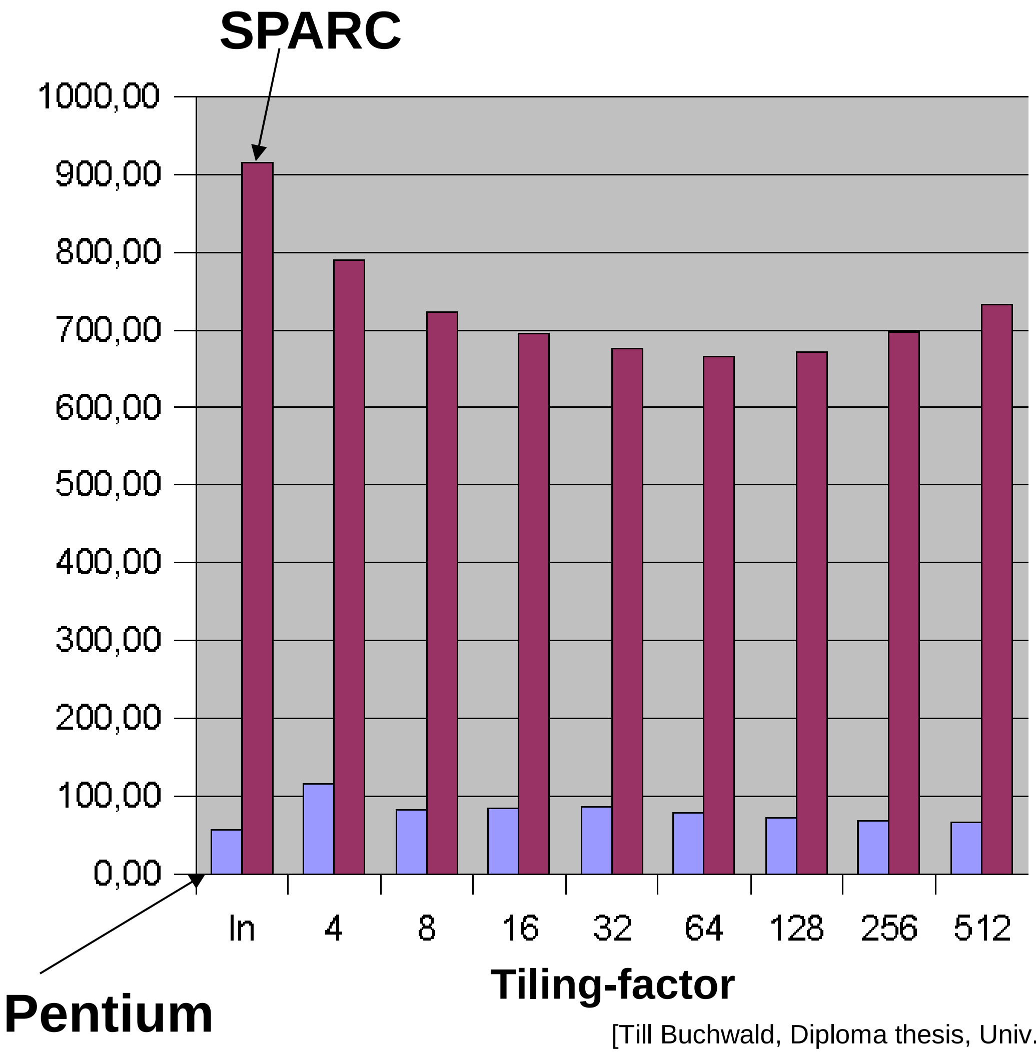
Same elements for next iteration of i



Monica Lam: The Cache Performance and Optimization of Blocked Algorithms, ASPLOS, 1991

Example

In practice, results by Buchwald are disappointing.
One of the few cases where an improvement was achieved:
Source: similar to matrix mult.



[Till Buchwald, Diploma thesis, Univ. Dortmund, Informatik 12, 12/2004]

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Transformation “Loop nest splitting”

Example: Separation of margin handling

many if-statements for margin-checking

no checking, efficient

+

only few margin elements to be processed

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Loop nest splitting at University of Dortmund

Loop nest from MPEG-4 full search motion estimation

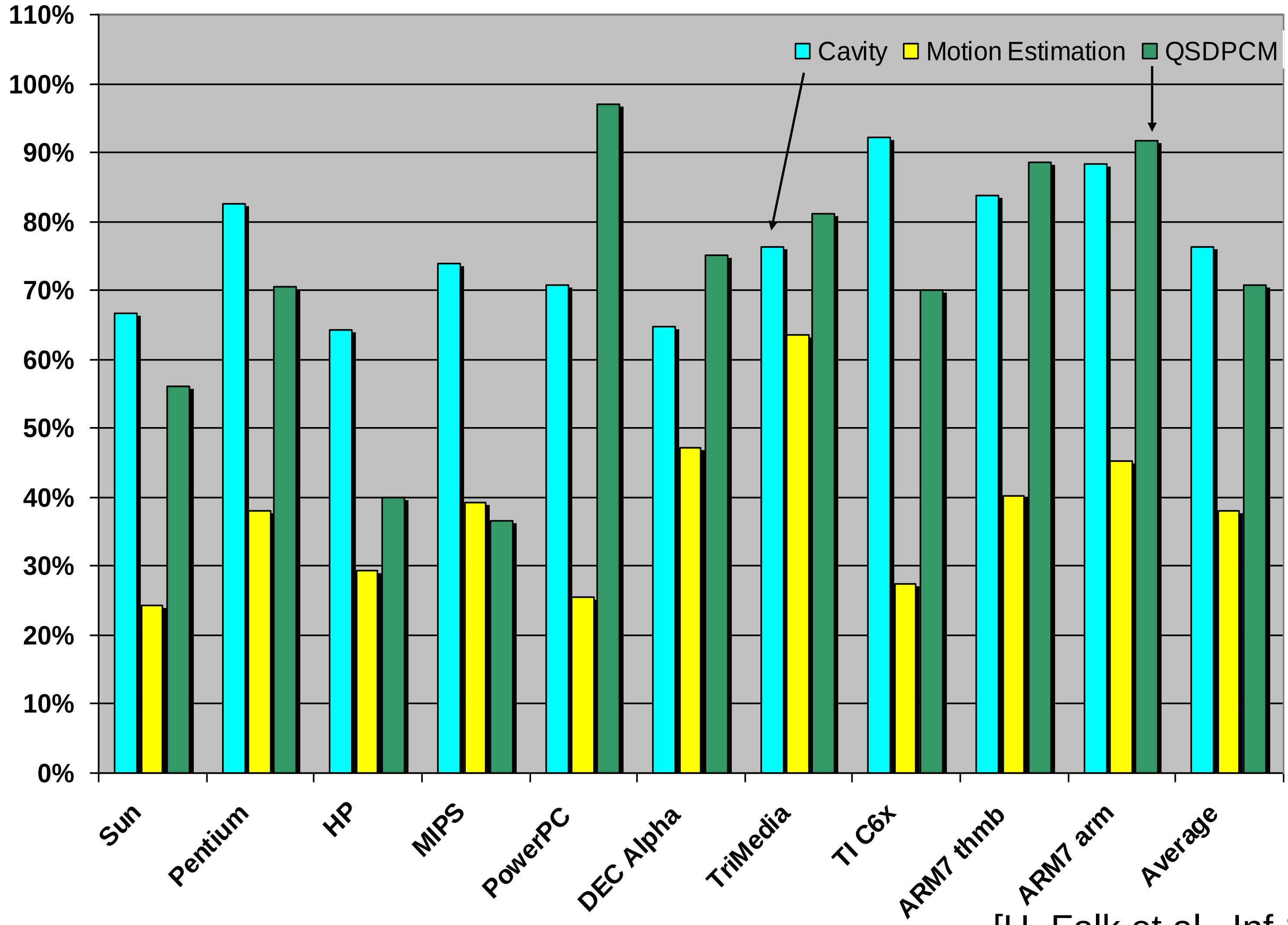
```
for (z=0; z<20; z++)
 for (x=0; x<36; x++) {x1=4*x;
  for (y=0; y<49; y++) {y1=4*y;
   for (k=0; k<9; k++) {x2=x1+k-4;
    for (l=0; l<9; ) {y2=y1+l-4;
     for (i=0; i<4; i++) {x3=x1+i; x4=x2+i;
      for (j=0; j<4;j++) {y3=y1+j; y4=y2+j;
       if (x3<0 || 35<x3||y3<0||48<y3)
        then_block_1; else else_block_1;
       if (x4<0|| 35<x4||y4<0||48<y4)
        then_block_2; else else_block_2;
}}}}}}
```

analysis of polyhedral domains,
selection with genetic algorithm

```
for (z=0; z<20; z++)
 for (x=0; x<36; x++) {x1=4*x;
  for (y=0; y<49; y++)
if (x>=10||y>=14)
  for (; y<49; y++)
    for (k=0; k<9; k++)
      for (l=0; l<9;l++ )
       for (i=0; i<4; i++)
        for (j=0; j<4;j++) {
         then_block_1; then_block_2}
else {y1=4*y;
  for (k=0; k<9; k++) {x2=x1+k-4;
    for (l=0; l<9; ) {y2=y1+l-4;
     for (i=0; i<4; i++) {x3=x1+i; x4=x2+i;
      for (j=0; j<4;j++) {y3=y1+j; y4=y2+j;
       if (0 || 35<x3 ||0 || 48<y3)
        then-block-1; else else-block-1;
       if (x4<0|| 35<x4||y4<0||48<y4)
        then_block_2; else else_block_2;
}}}}}}
```

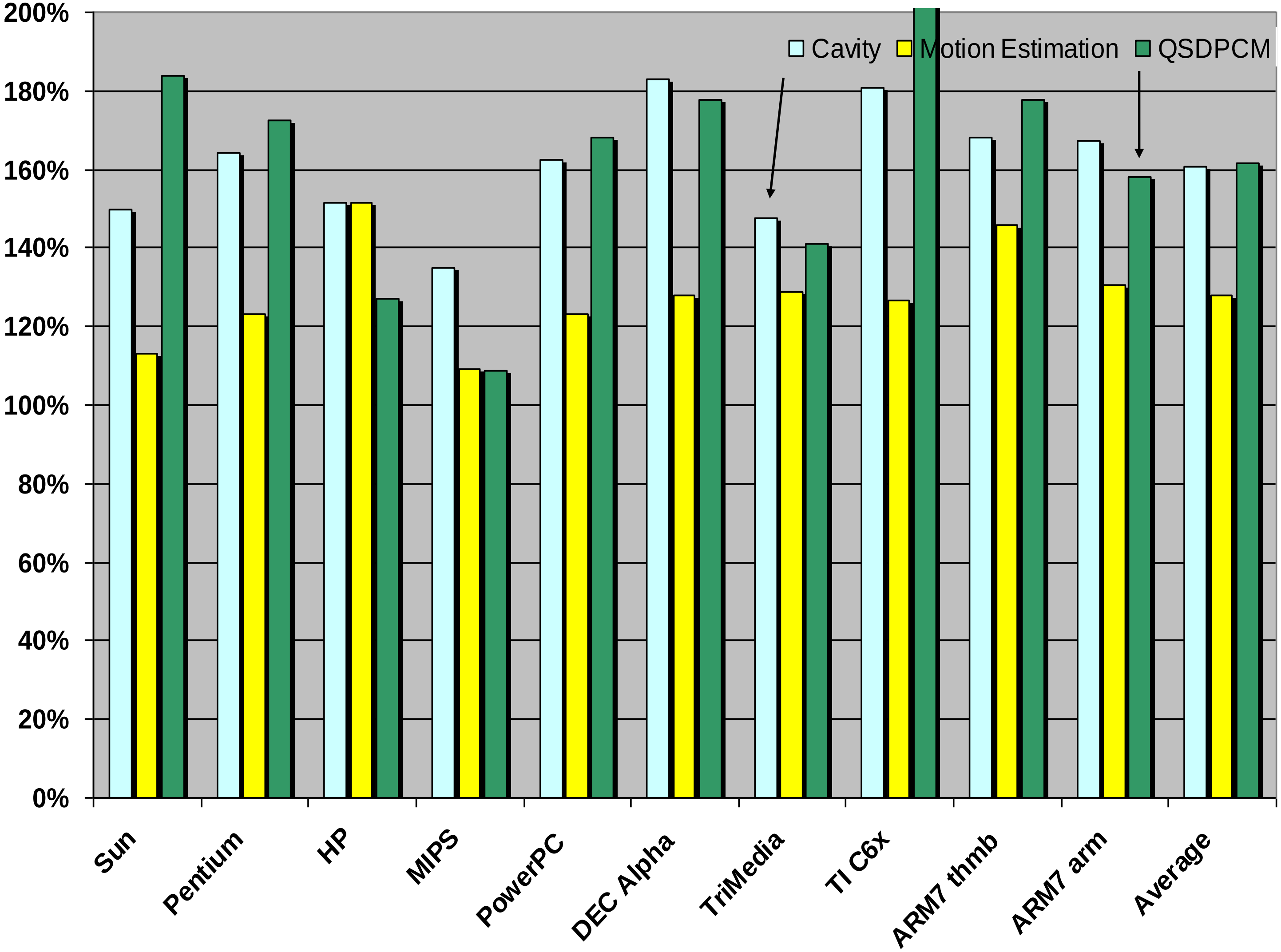
[H. Falk et al., Inf 12, UniDo, 2002]

Results for loop nest splitting
- Execution times -



[H. Falk et al., Inf 12, UniDo, 2002]

Results for loop nest splitting
- Code sizes -



[Falk, 2002]

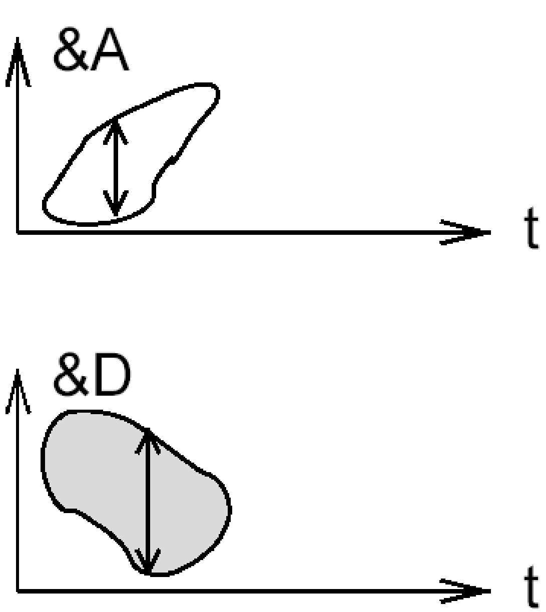
High-level optimizations

Book section 7.2

- Floating-point to fixed point conversion
- Simple loop transformations
- Loop tiling/blocking
- Loop (nest) splitting
- Array folding

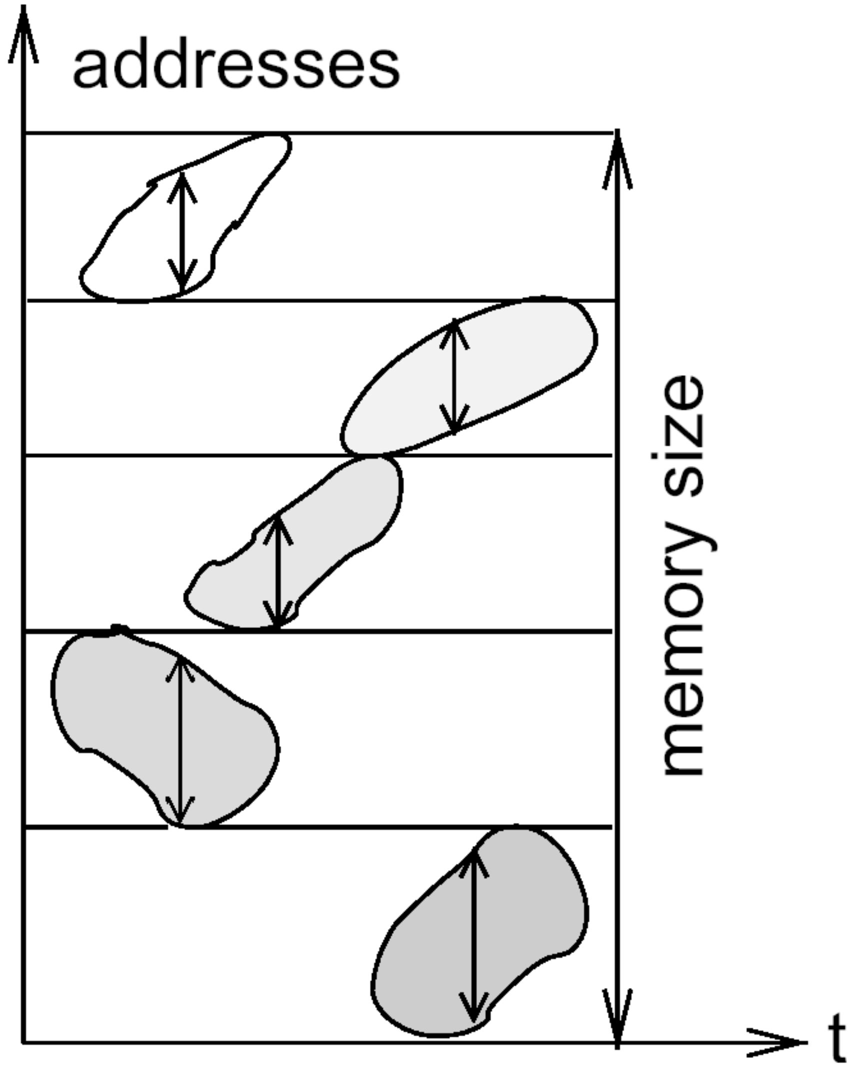
Array folding

Initial arrays



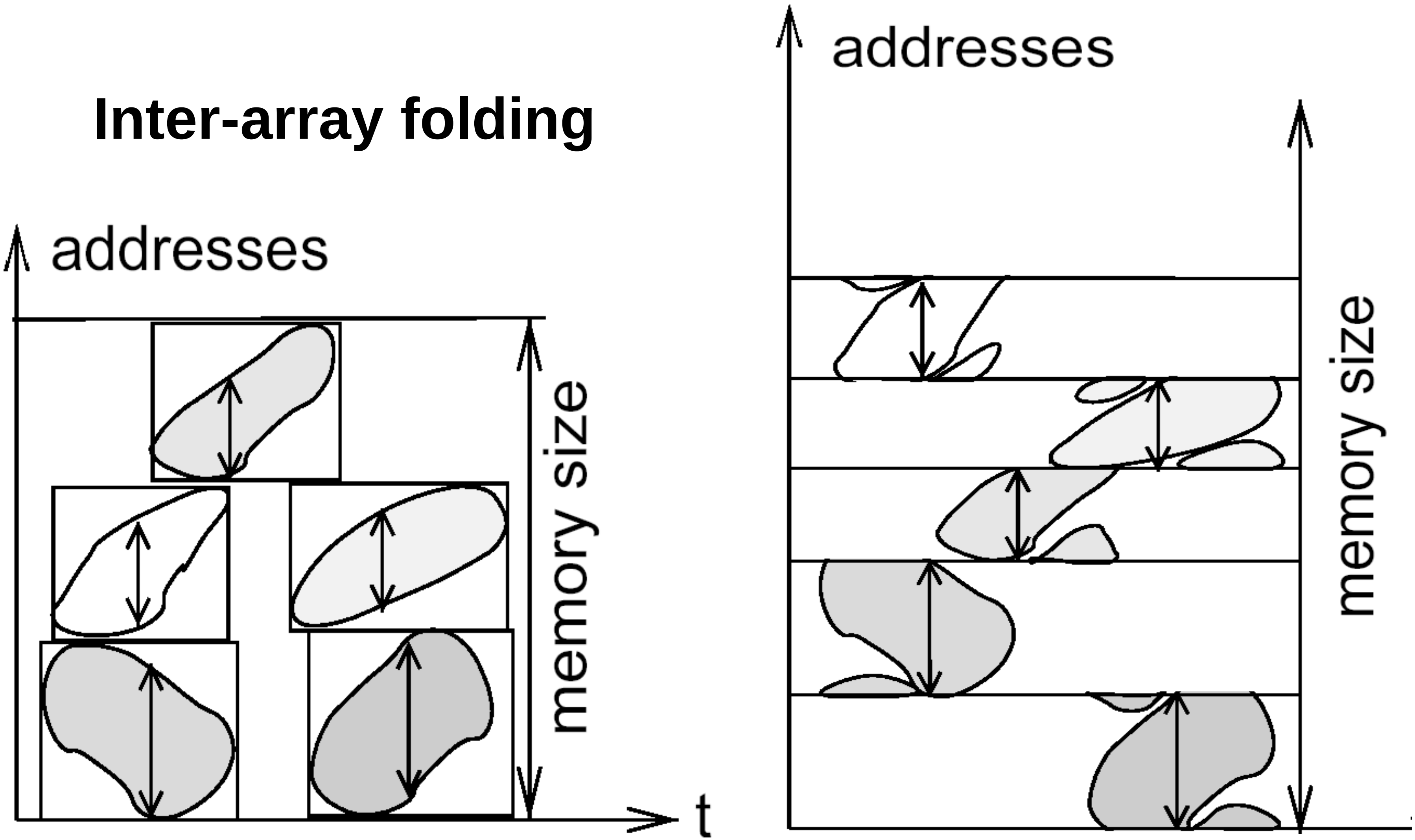
Array folding

Unfolded arrays



Intra-array folding

Inter-array folding

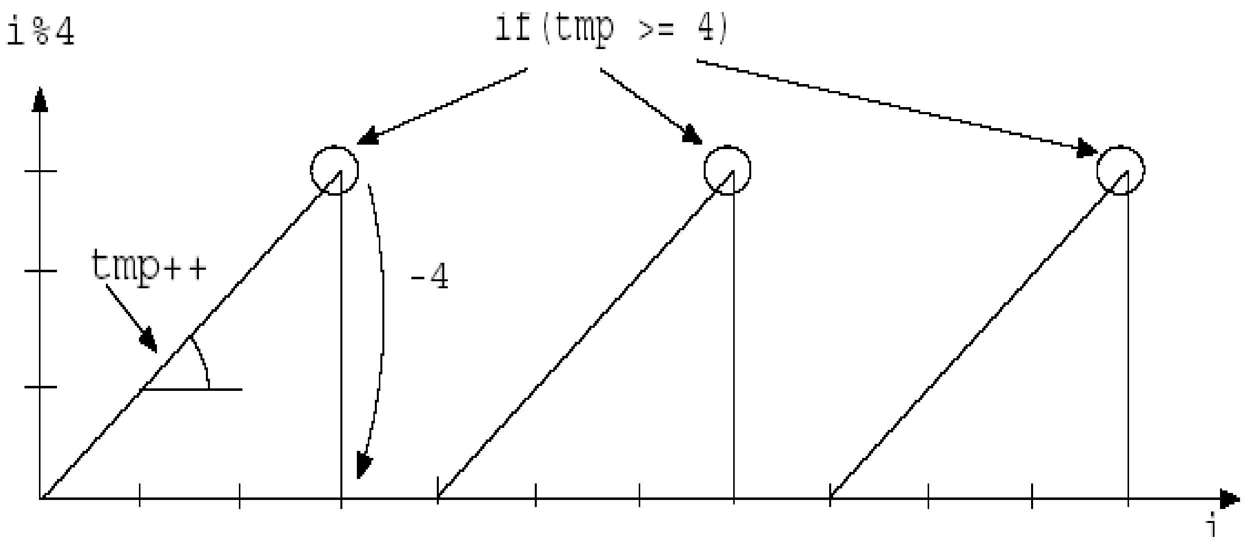


Application

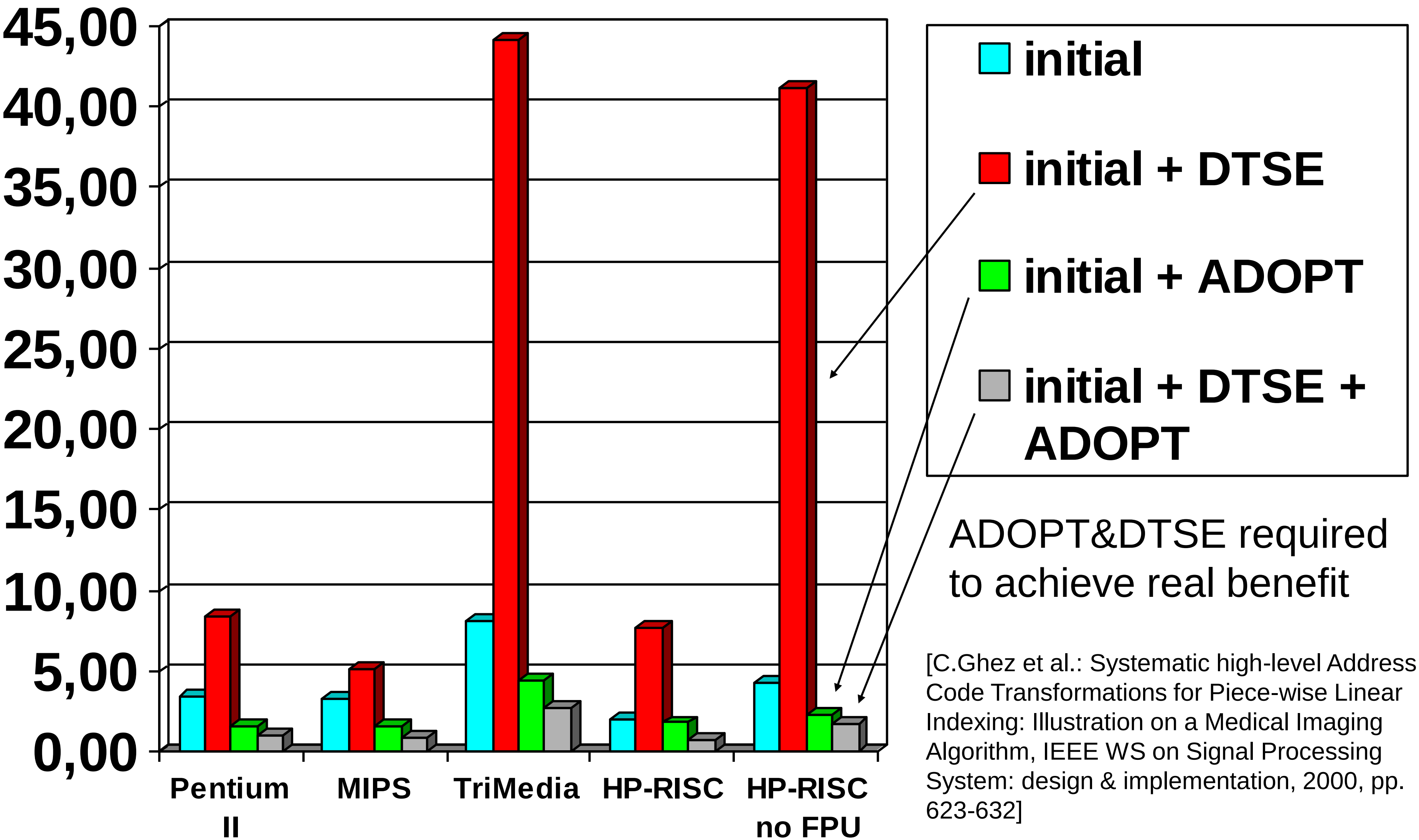
- Array folding is implemented in the DTSE optimization proposed by IMEC. Array folding adds div and mod ops. Optimizations required to remove these costly operations.
- At IMEC, ADOPT address optimizations perform this task. For example, modulo operations are replaced by pointers (indexes) which are incremented and reset.

```
for(i=0; i<20; i++)
      B[i % 4];

tmp=0;
for(i=0; i<20; i++)
      if(tmp >= 4)
         tmp -=4;
      B[tmp];
      tmp ++;
```



Results (Mcycles for cavity benchmark)



ADOPT&DTSE required to achieve real benefit

[C.Ghez et al.: Systematic high-level Address Code Transformations for Piece-wise Linear Indexing: Illustration on a Medical Imaging Algorithm, IEEE WS on Signal Processing System: design & implementation, 2000, pp. 623-632]

Summary

- Task concurrency management
  - Re-partitioning of computations into tasks
- Floating-point to fixed point conversion
  - Range estimation
  - Conversion
  - Analysis of the results
- High-level loop transformations
  - Fusion
  - Unrolling
  - Tiling
  - Loop nest splitting
  - Array folding

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