Вспомогательные материалы для преподавателя

Особенности векторизации кода

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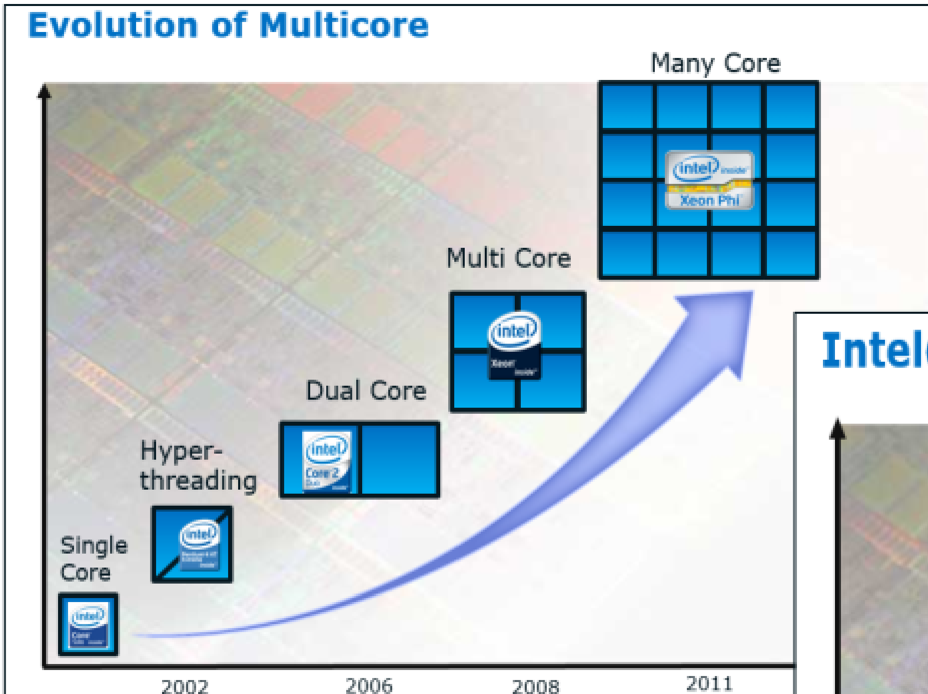
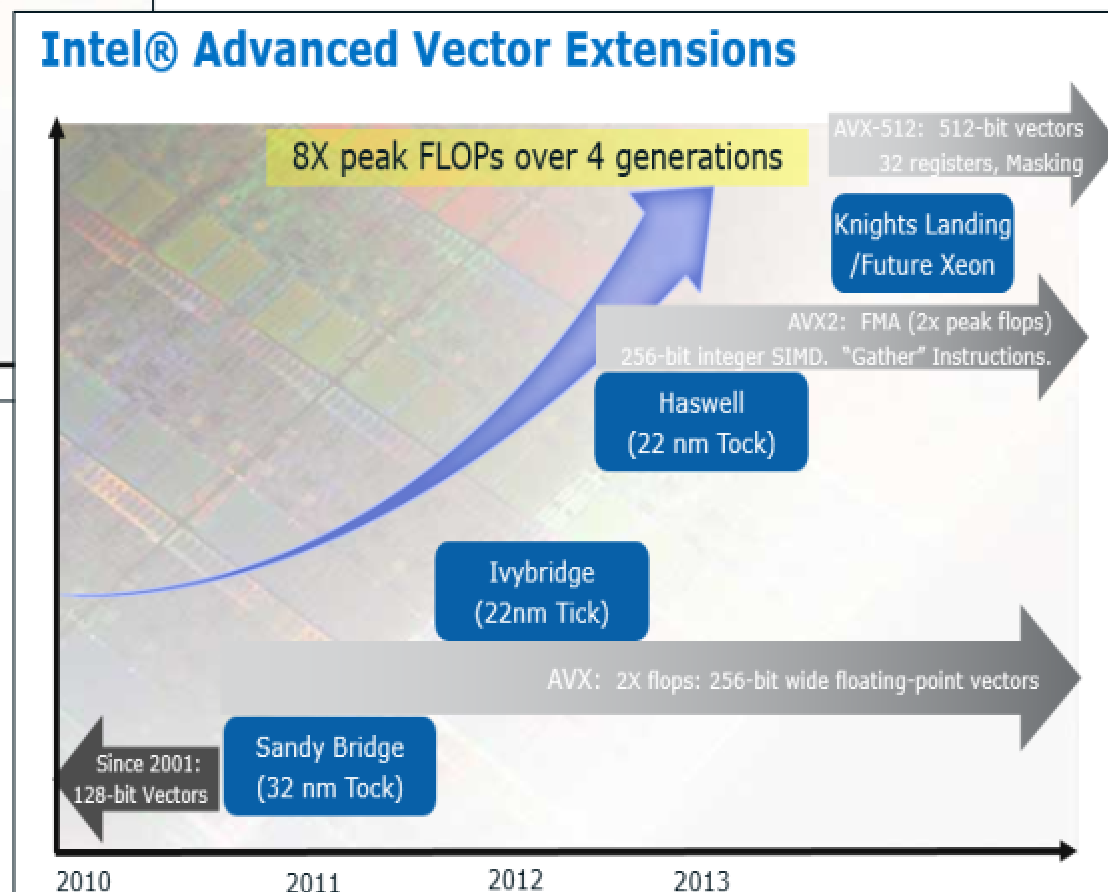
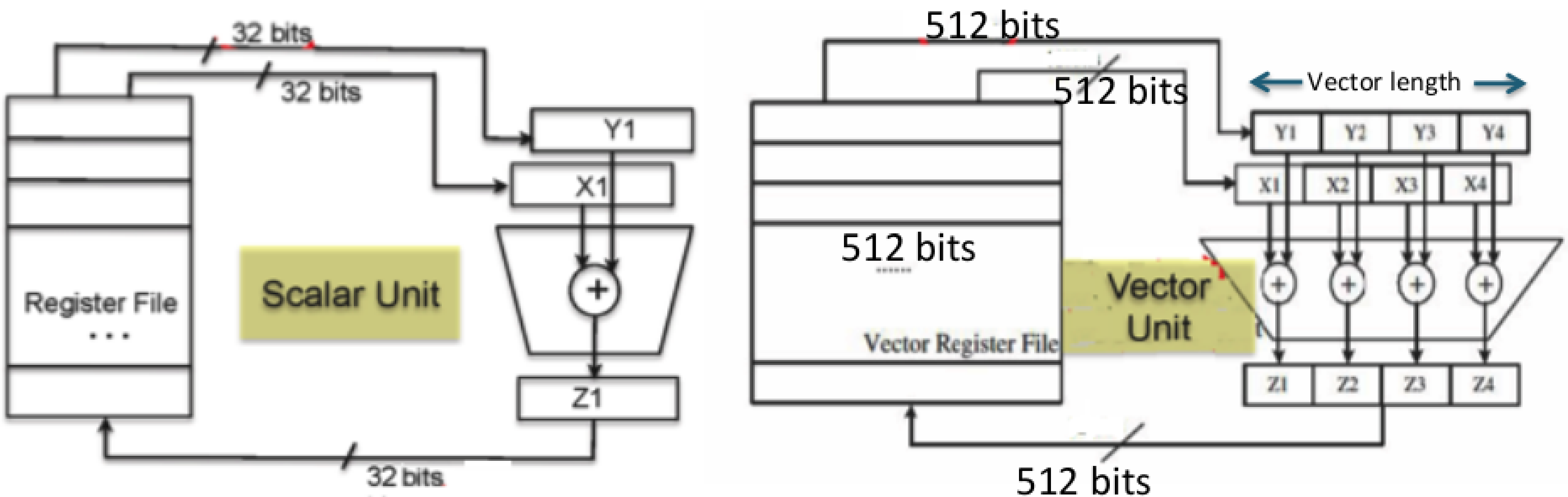
Эволюция архитектур



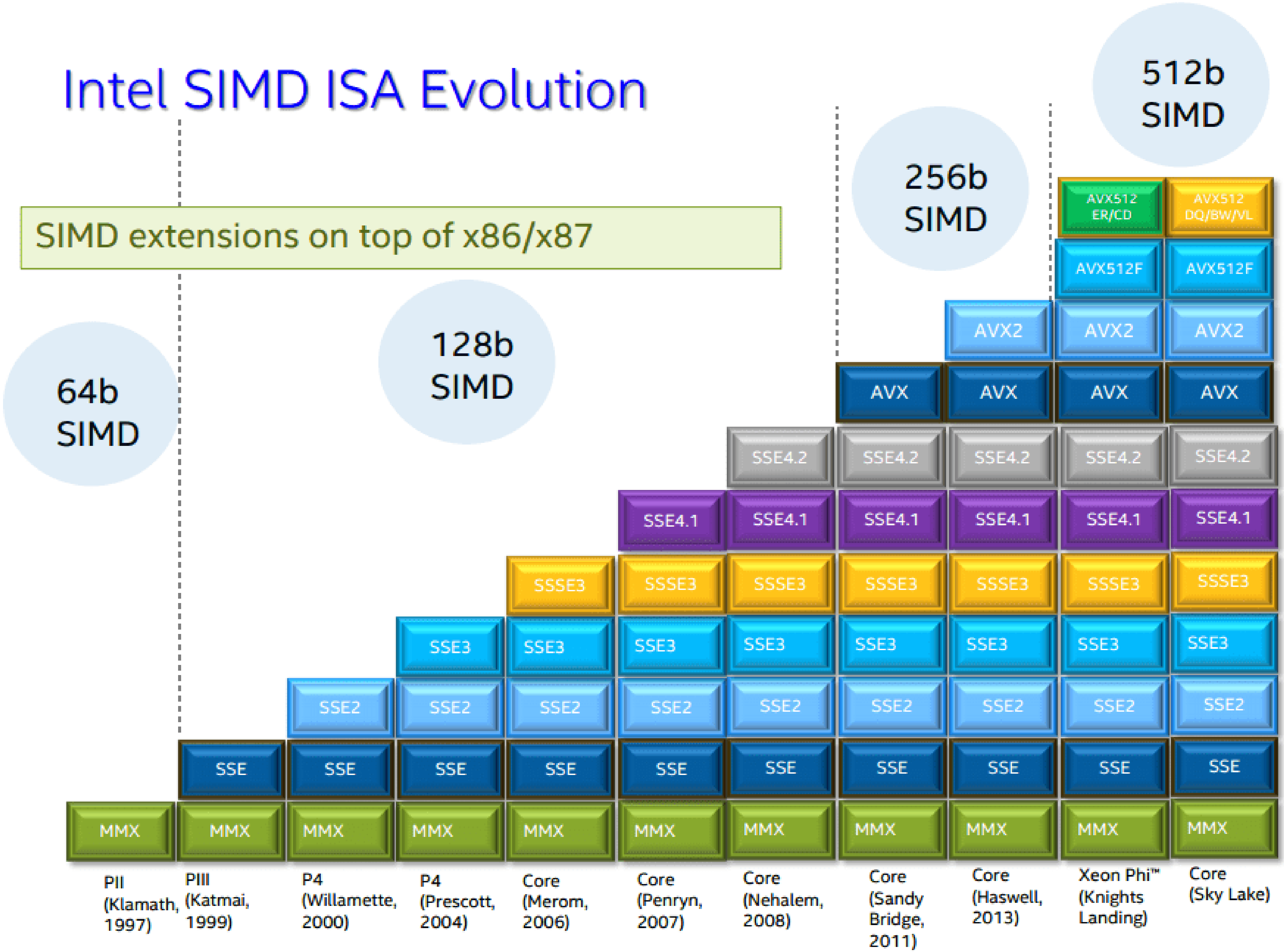
All future processors will have multiple cores with SIMD instructions



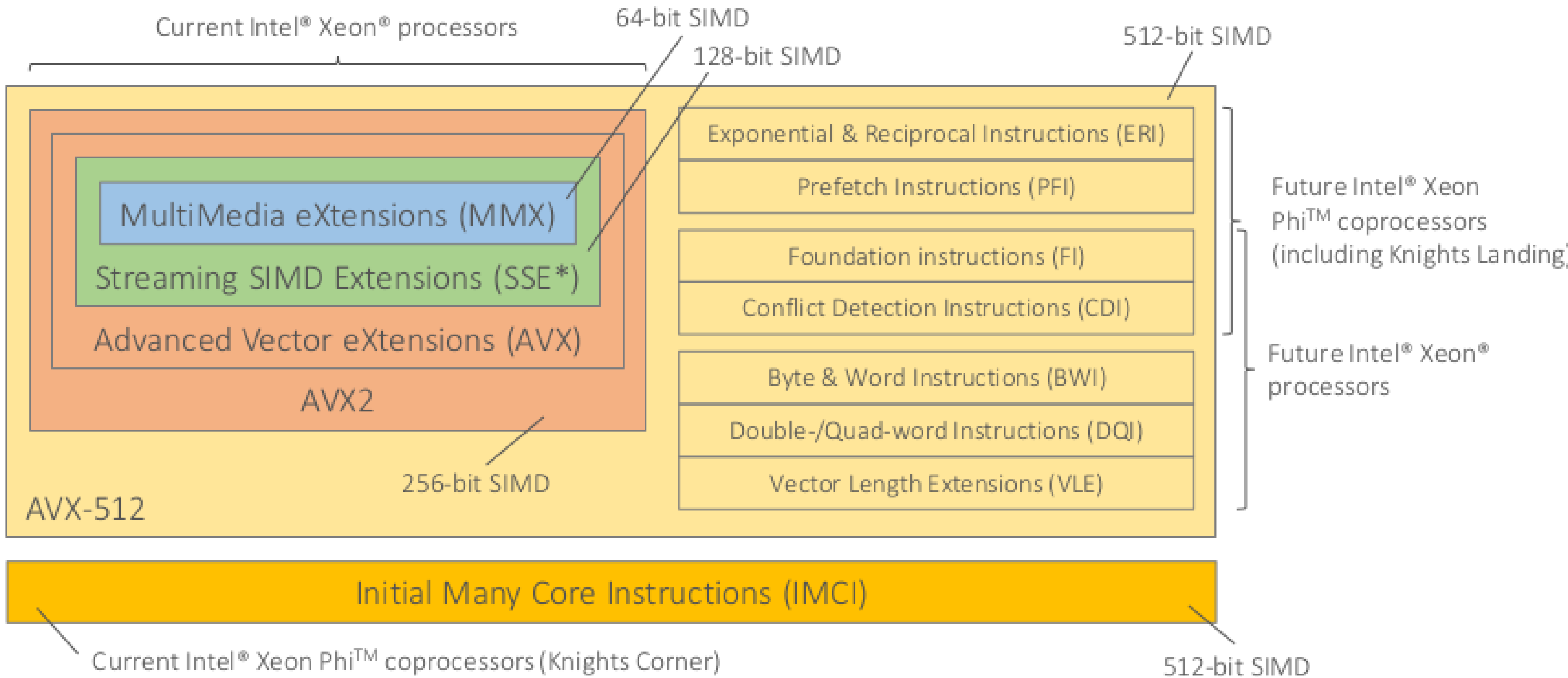
Архитектуры SIMD современных ядер



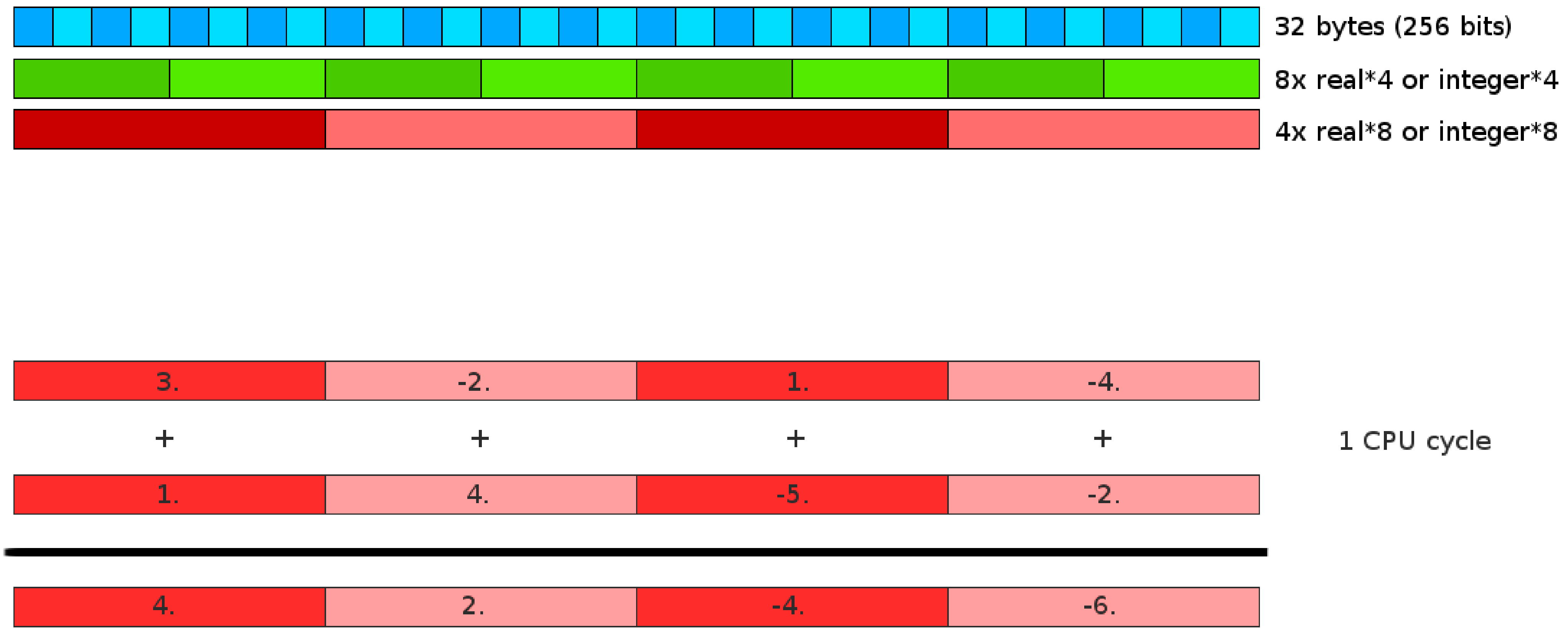
Intel SIMD ISA Evolution



Типы инструкций SIMD у решений Intel



Различия для разновидностей типа



Трансформация кода

```
DO I = 1, N
   Z(I) = X(I) + Y(I)
ENDDO
```

```
DO I = 1, N, 4
  Z(I)   =   X(I) +   Y(I)
  Z(I+1) = X(I+1) + Y(I+1)
  Z(I+2) = X(I+2) + Y(I+2)
  Z(I+3) = X(I+3) + Y(I+3)
ENDDO
```

```
VLOAD  X(I), X(I+1), X(I+2), X(I+3)
VLOAD  Y(I), Y(I+1), Y(I+2), Y(I+3)
VADD   Z(I, ..., I+3)   X+Y(I, ..., I+3)
VSTORE Z(I), Z(I+1), Z(I+2), Z(I+3)
```

Изменение порядка выполнения

```
DO I = 1, 4
  A(I) = B(I) + C(I)
  D(I) = E(I) + F(I)
END DO
```

Non-Vector

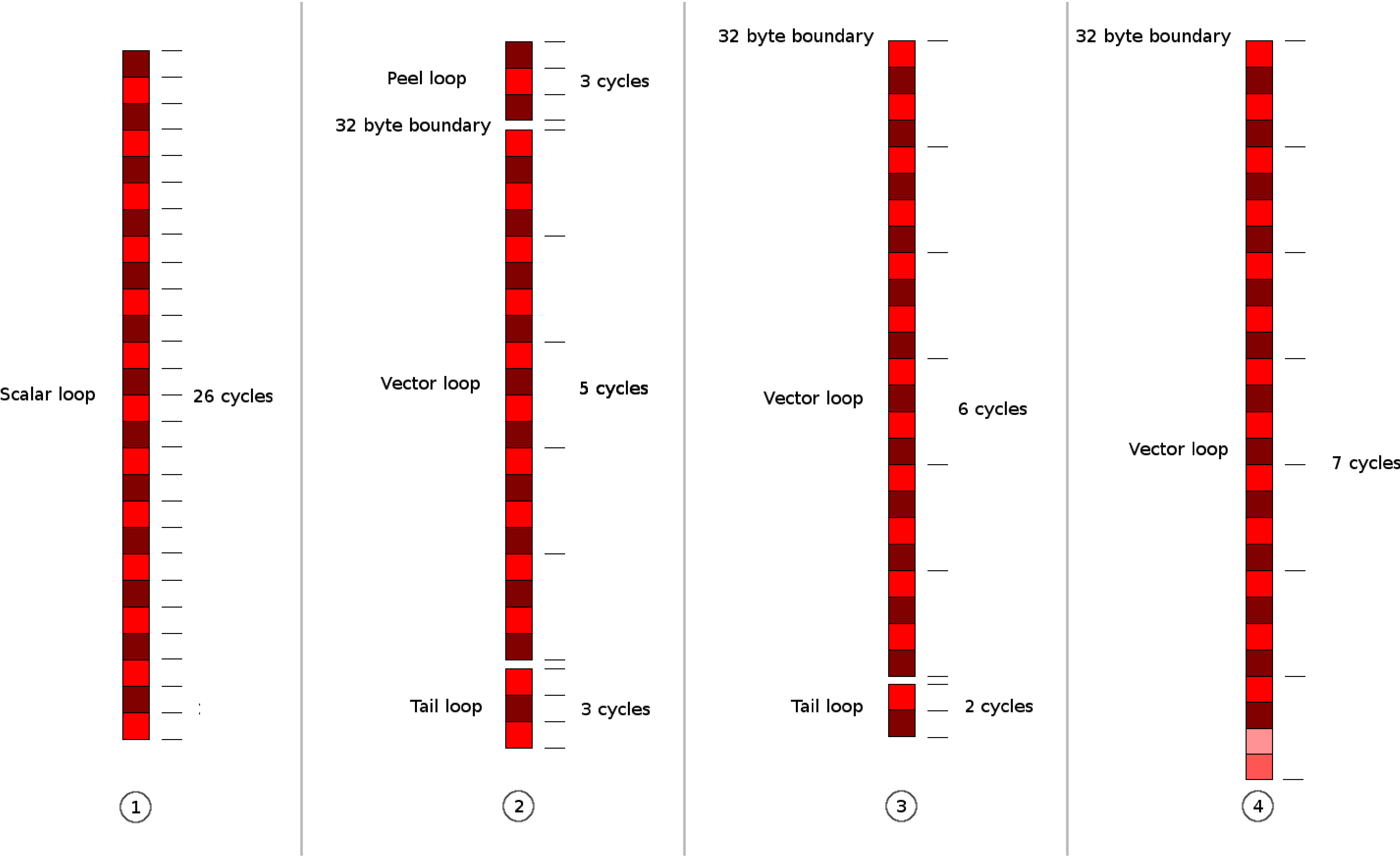
```
A(1) = B(1) + C(1)
 D(1) = E(1) + F(1)
A(2) = B(2) + C(2)
 D(2) = E(2) + F(2)
A(3) = B(3) + C(3)
 D(3) = E(3) + F(3)
A(4) = B(4) + C(4)
 D(4) = E(4) + F(4)
```

Vector

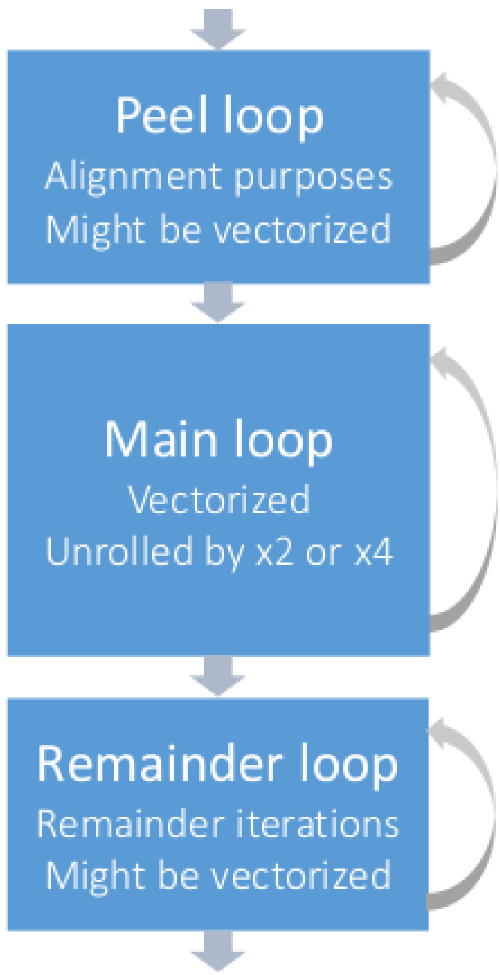
```
A(1) = B(1) + C(1)
A(2) = B(2) + C(2)
A(3) = B(3) + C(3)
A(4) = B(4) + C(4)
 D(1) = E(1) + F(1)
 D(2) = E(2) + F(2)
 D(3) = E(3) + F(3)
 D(4) = E(4) + F(4)
```

Order of execution

Три части порождаемого цикла



Три части порождаемого цикла




```
LOOP BEGIN at gas_dyn2.f90(2330,26)
<Peeled>
   remark #15389: vectorization support: reference AMAC1U has unaligned access
   remark #15381: vectorization support: unaligned access used inside loop body
   remark #15301: PEEL LOOP WAS VECTORIZED
LOOP END

LOOP BEGIN at gas_dyn2.f90(2330,26)
   remark #25084: Preprocess Loopnests: Moving Out Store
   remark #15388: vectorization support: reference AMAC1U has aligned access
   remark #15399: vectorization support: unroll factor set to 2
   remark #15300: LOOP WAS VECTORIZED
   remark #15475: --- begin vector loop cost summary ---
   remark #15476: scalar loop cost: 8
   remark #15477: vector loop cost: 0.620
   remark #15478: estimated potential speedup: 15.890
   remark #15479: lightweight vector operations: 5
   remark #15488: --- end vector loop cost summary ---
   remark #25018: Total number of lines prefetched=4
   remark #25019: Number of spatial prefetches=4, dist=8
   remark #25021: Number of initial-value prefetches=6
LOOP END

LOOP BEGIN at gas_dyn2.f90(2330,26)
<Remainder>
   remark #15388: vectorization support: reference AMAC1U has aligned access
   remark #15388: vectorization support: reference AMAC1U has aligned access
   remark #15301: REMAINDER LOOP WAS VECTORIZED
LOOP END
```

Условия векторизации

- Данные должны быть сплошными в памяти
- Первый элемент каждого вектора должен быть выровнен
- Не должно быть перекрытий по памяти
- Не должно быть зависимостей итераций в виде чтение-после-записи

На что обращать внимание в коде

```
for (int i = 0; i < N; i++)
    a[i] = a[i-1] + b[i];
```

```
for (int i = 0; i < N; i++)
    a[c[i]] = b[d[i]];
```

```
for (int i = 0; i < N; i++)
    a[i] = foo(b[i]);
```

Для C99 и C++

```
void v_add(float *restrict c,
           float *restrict a,
           float *restrict b)
{
    for (int i = 0; i < N; i++)
        c[i] = a[i] + b[i];
}
```

```
void v_add(float *c, float *a, float *b)
{
#pragma ivdep
    for (int i = 0; i < N; i++)
        c[i] = a[i] + b[i];
}
```

Управляемая векторизация: циклы

```
void v_add(float *c, float *a, float *b)
{
#pragma simd
    for (int i = 0; i < N; i++)
        c[i] = a[i] + b[i];
}
```

Управляемая векторизация: OpenMP

```
#pragma omp simd reduction(+:sum) aligned(a : 64)
for(i = 0; i < num; i++) {
 a[i] = b[i] * c[i];
 sum = sum + a[i];
}
```

Управляемая векторизация: функции

```
__declspec(vector)
void v_add(float c, float a, float b)
{
     c = a + b;
}
     …
for (int i = 0; i < N; i++)
     v_add(C[i], A[i], B[i]);
```

Управляемая векторизация: функции (Fortran)

```
module fofx
contains
  function f(x)
!dir$ attributes vector :: f
    real, intent(in) :: x
    real f
    f = cos(x * x + 1.) / (x * x + 1.)
  end function
end module

program main
  use fofx
  real a(100), x(100)
  ...
  do i=1,100
    a(i) = f(x(i))
  end do
  ...
end program
```

Line 7

Elemental function in vectorization sense

```
$ ifort –vec-report=3 elemental.f90
...
elemental.f90(67): (col. 11) remark: LOOP WAS
VECTORIZED
...
elemental.f90(7): (col. 18) remark: FUNCTION WAS
VECTORIZED
elemental.f90(7): (col. 18) remark: FUNCTION WAS
VECTORIZED
```

Line 67

Управляемая векторизация: функции (Fortran)

```
module fofx
contains
  elemental function f(x)
!dir$ attributes vector :: f
    real, intent(in) :: x
    real f
    f = cos(x * x + 1.) / (x * x + 1.)
  end function
end module

program main
  use fofx
  real a(100), x(100)
  ...
  a = f(x)
  ...
end program
```

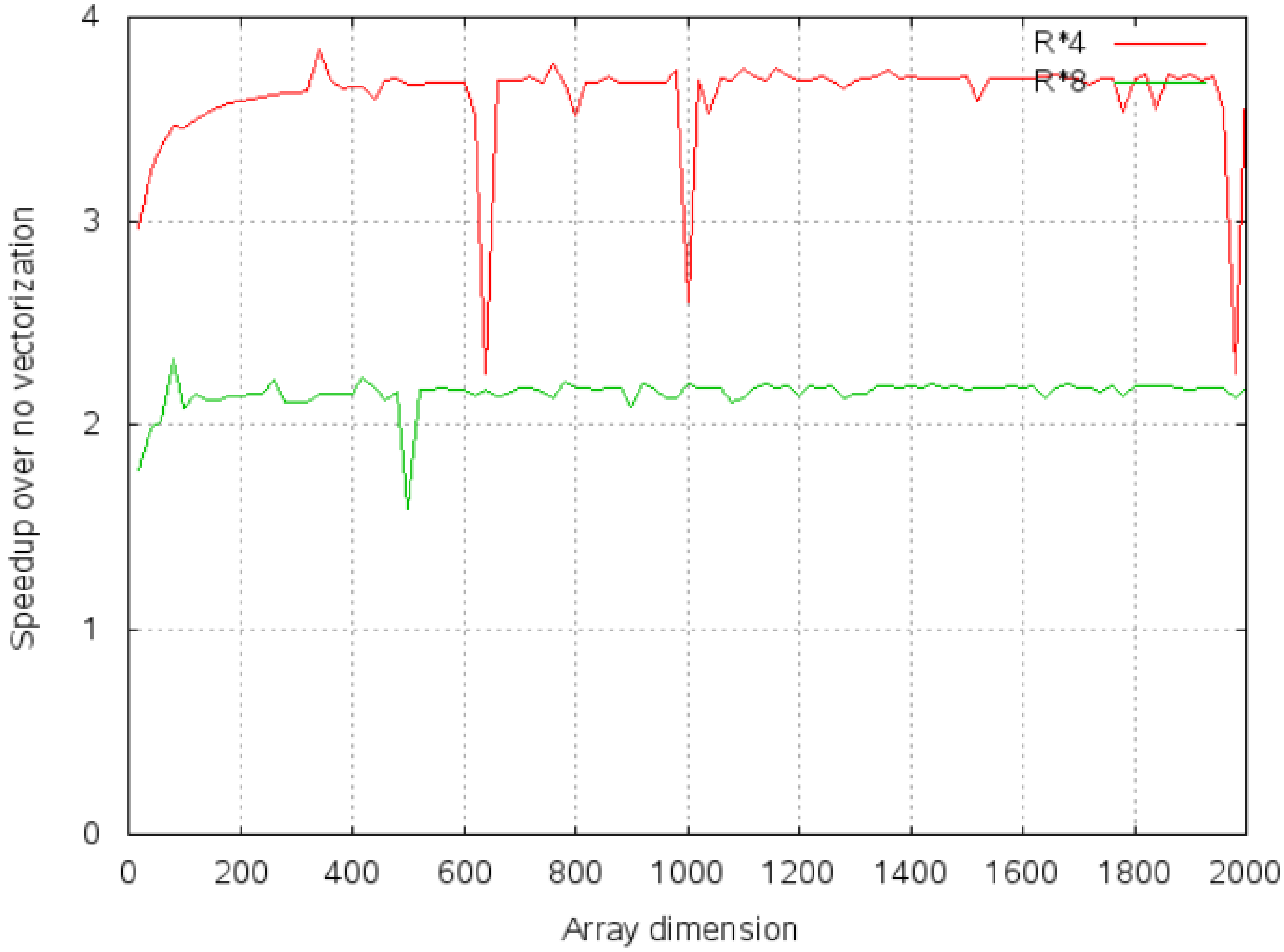
This Fortran 'elemental' clause nothing to do with vect.

Elemental function in vectorization sense

Line 67

```
$ ifort –vec-report=3 elemental.f90
...
elemental.f90(67): (col. 11) remark: LOOP WAS
VECTORIZED
...
elemental.f90(7): (col. 28) remark: FUNCTION WAS
VECTORIZED
elemental.f90(7): (col. 28) remark: FUNCTION WAS
VECTORIZED
```

Прирост производительности для элементных функций



Управляемая векторизация: OpenMP

```
#pragma omp parallel for simd
for(i = 0; i < num; i++) {
 sum = sum + a[i];
}
```

Управляемая векторизация: OpenMP

```
#pragma omp declare simd
float myfunction(float a, float b, float c )
{
 return a * b + c ;
}
```

```
#pragma omp simd
for(i = 0; i < num; i++) {
 OUT[i] = myfunction(arraya[i], arrayb[i], arrayc[i]);
}
```

Явная векторизация

```
a[:]        // All elements
a[2:6]      // Elements 2 to 7
a[:][5]     // Column 5
a[0:3:2]    // Elements 0,2,4
```

```
__declspec(vector)
void v_add(float c, float a, float b)
{
    c = a + b;
}
    …
v_add(C[:], A[:], B[:]);
```

Массивы структур и структуры массивов

```
// Array of Structures (AoS)
struct coordinate {
     float x, y, z;
} crd[N];
     …
for (int i = 0; i < N; i++)
     … = … f(crd[i].x, crd[i],y, crd[i].z);
```

Consecutive elements in memory →

x0	y0	z0	x1	y1	z1	…	x(n-1)	y(n-1)	z(n-1)

```
// Structure of Arrays (SoA)
struct coordinate {
     float x[N], y[N], z[N];
} crd;
     …
for (int i = 0; i < N; i++)
     … = … f(crd.x[i], crd.y[i], crd.z[i]);
```

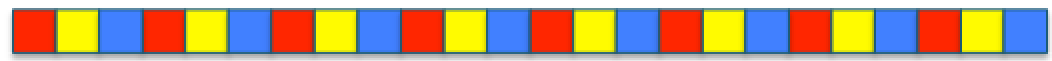
Consecutive elements in memory →

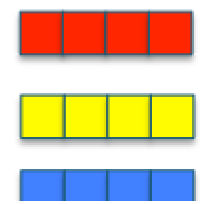
x0	x1	…	x(n-1)	y0	y1	…	y(n-1)	z0	z1	…	z(n-1)

Массив структур

```
type coords
  real :: x, y, z
end type
type (coords) :: p(100)
real dsquared(100)

do i=1,100
  dsquared(i) = p(i)%x**2 + p(i)%y**2 + p(i)%z**2
end do
```

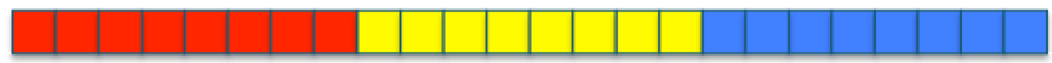


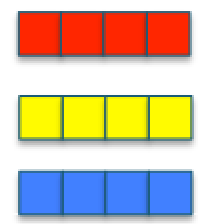


Структура массивов

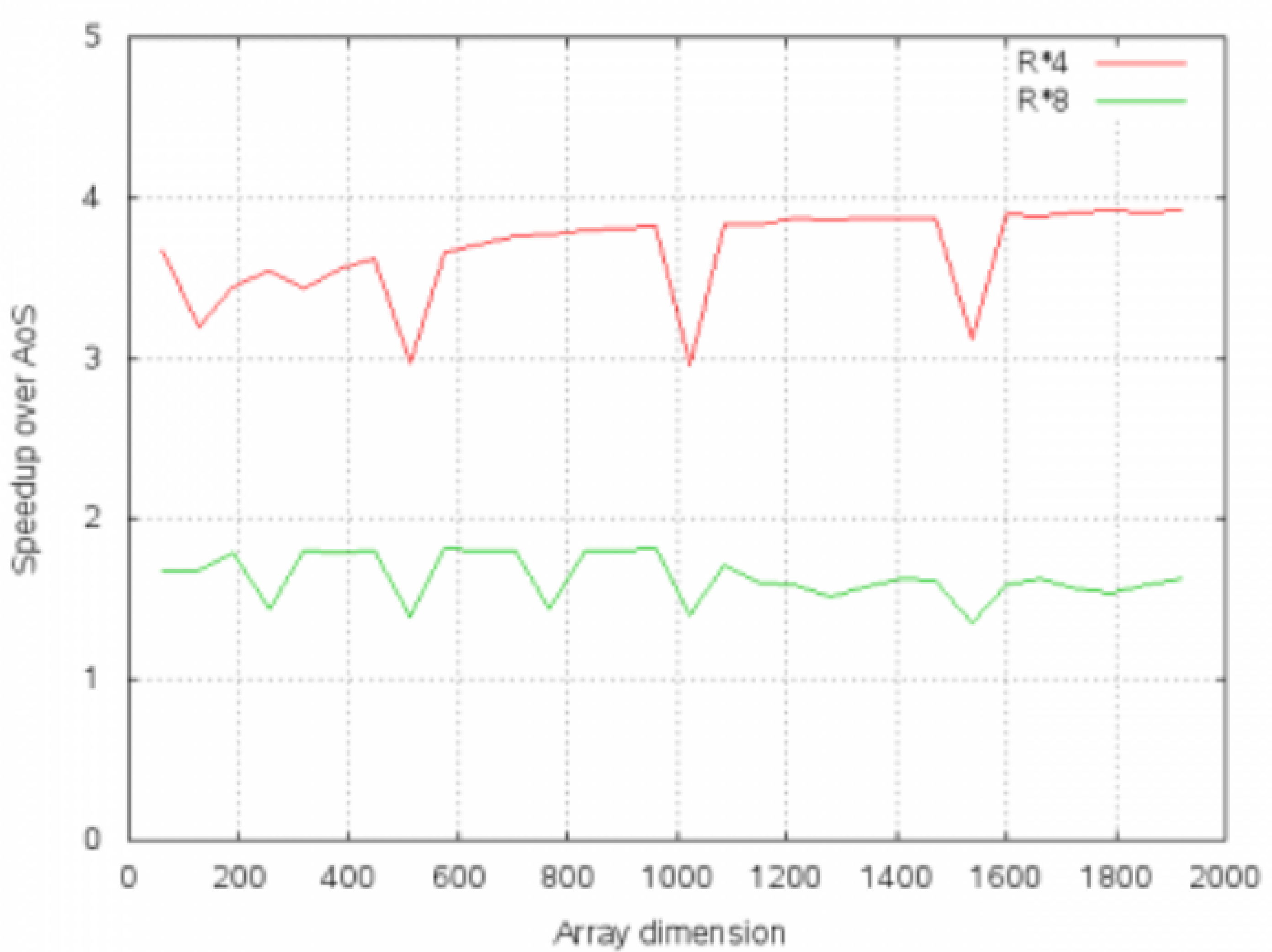
```
type coords
  real :: x(100), y(100), z(100)
end type
type (coords) :: p
real dsquared(100)

do i=1,100
  dsquared(i) = p%x(i)**2 + p%y(i)**2 + p%z(i)**2
end do
```





Прирост производительности для структуры массивов



Используйте средства компиляторов

```
edison11 h/hjw> cc -vec-report=6 -c mm.c
mm.c(7): (col. 2) remark: loop was not vectorized: loop was transformed to memset or memcpy
mm.c(10): (col. 2) remark: vectorization support: reference c has aligned access
mm.c(10): (col. 2) remark: vectorization support: reference c has aligned access
mm.c(10): (col. 2) remark: vectorization support: reference a has aligned access
mm.c(6): (col. 2) remark: vectorization support: unroll factor set to 4
mm.c(6): (col. 2) remark: PERMUTED LOOP WAS VECTORIZED
mm.c(9): (col. 2) remark: loop was not vectorized: not inner loop
mm.c(7): (col. 2) remark: loop was not vectorized: not inner loop
```

Используйте средства компиляторов: Cray

```
57.  + 1-----------<        do it=1,itmax
58.  + 1 br4--------<          do j=1,n
59.  + 1 br4 b------<             do k=1,n
60.    1 br4 b Vr2--<                do i=1,nr
61.    1 br4 b Vr2                      c(i,j) = c(i,j) + a(i,k) * b(k,j)
62.    1 br4 b Vr2-->                end do
63.    1 br4 b------>             end do
64.    1 br4-------->          end do
65.    1------------>       end do
```

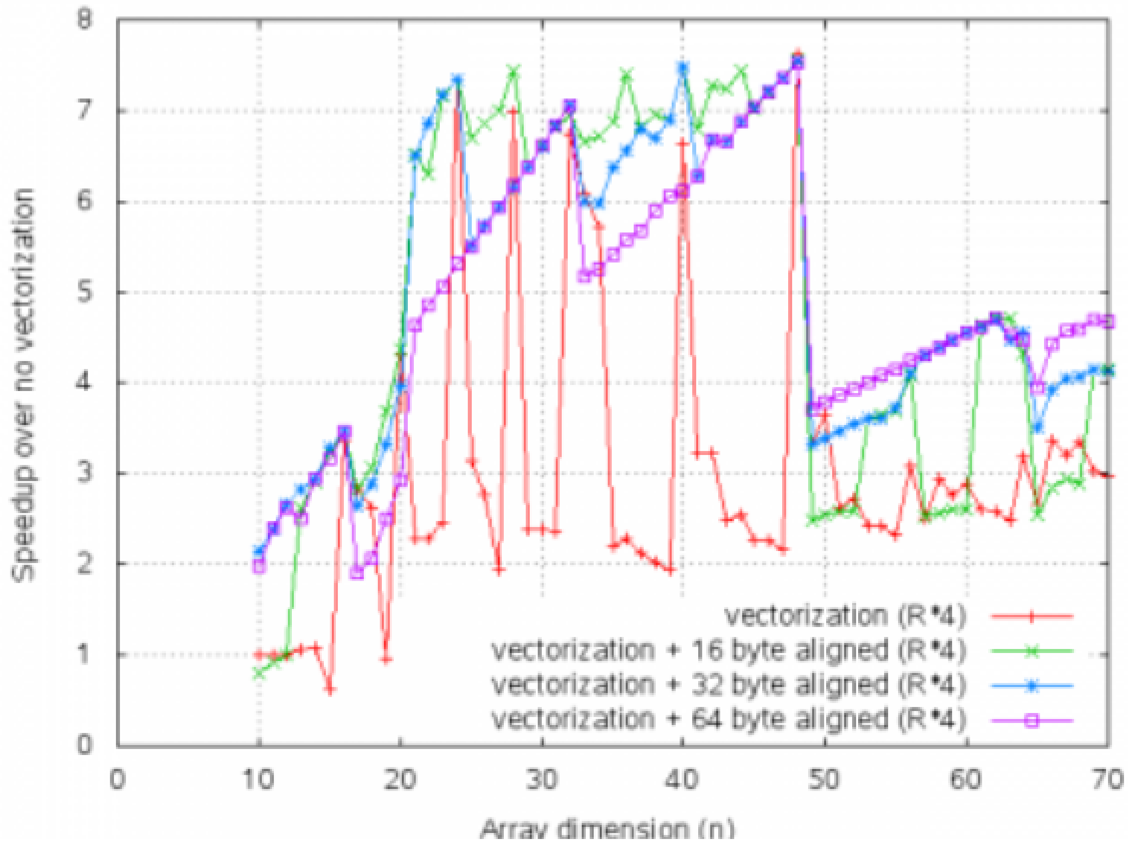
```
b - blocked
r - unrolled
V - Vectorized
```

```
ftn-6254 ftn: VECTOR File = matmat.F, Line = 57
  A loop starting at line 57 was not vectorized because a recurrence was found on "c" at line 61
ftn-6294 ftn: VECTOR File = matmat.F, Line = 58
  A loop starting at line 58 was not vectorized because a better candidate was found at line 60.
ftn-6049 ftn: SCALAR File = matmat.F, Line = 58
  A loop starting at line 58 was blocked with block size 8.
ftn-6005 ftn: SCALAR File = matmat.F, Line = 58
  A loop starting at line 58 was unrolled 4 times.
```

«Наивное» выравнивание данных

```
real, allocatable :: a(:,:), b(:,:), c(:,:)
!dir$ attributes align : 32 :: a,b,c
...
allocate (a(npadded,n))
allocate (b(npadded,n))
allocate (c(npadded,n))
...
do j=1,n
   do k=1,n
!dir$ vector aligned
      do i=1,npadded
         c(i,j) = c(i,j) &
            + a(i,k) * b(k,j)
      end do
   end do
end do

!... Ignore c(n+1:npadded,:)
```



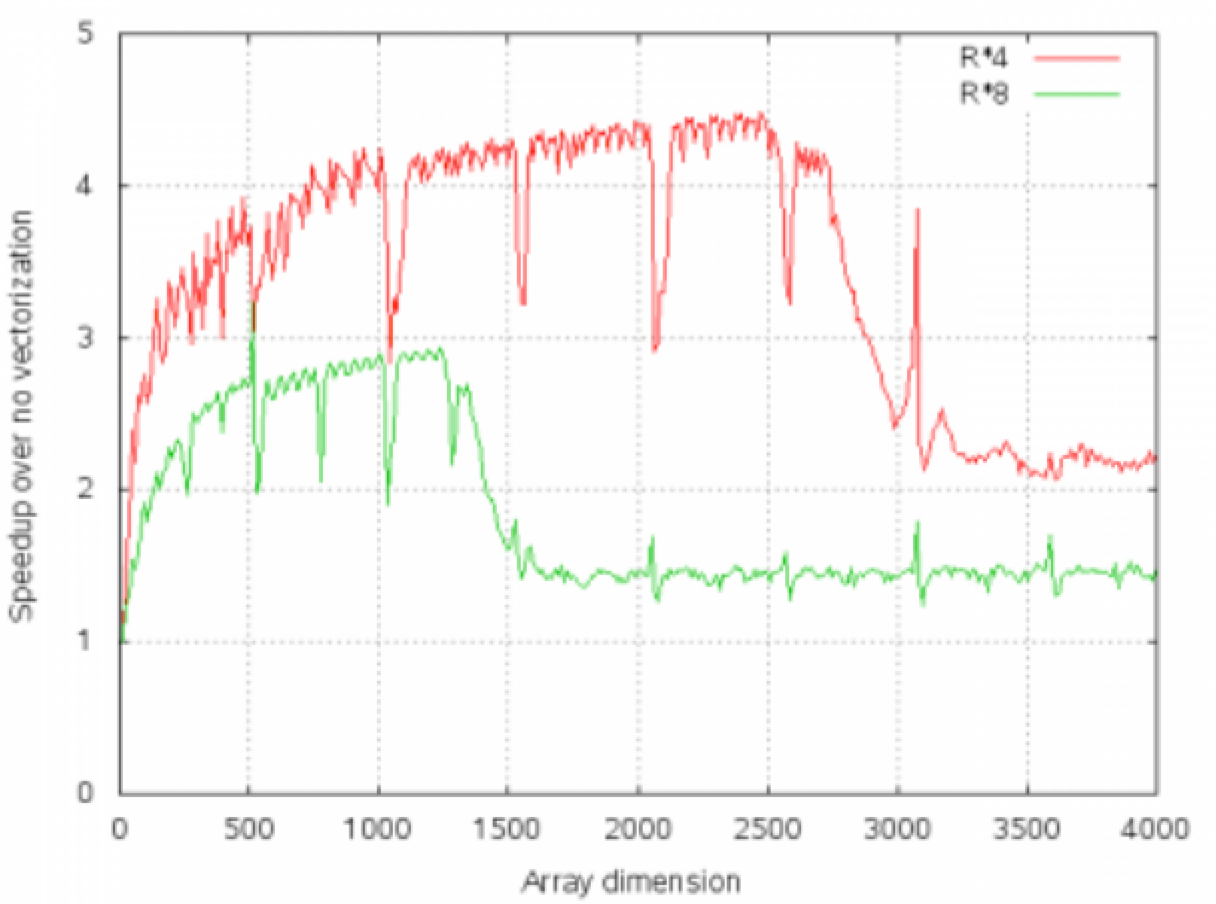
Выравнивание каждой строки

```
% cat Driver.c
...
#define COLBUF 1
...
#define COLWIDTH COL+COLBUF
...
        FTYPE a[ROW][COLWIDTH]  __attribute__((aligned(16)));
        FTYPE b[ROW]                    __attribute__((aligned(16)));
        FTYPE x[COLWIDTH]               __attribute__((aligned(16)));
...

% cat Multiply.c
...
#pragma vector aligned
...
                for (j = 0;j < size2; j++) {
                        b[i] += a[i][j] * x[j];
                }
```

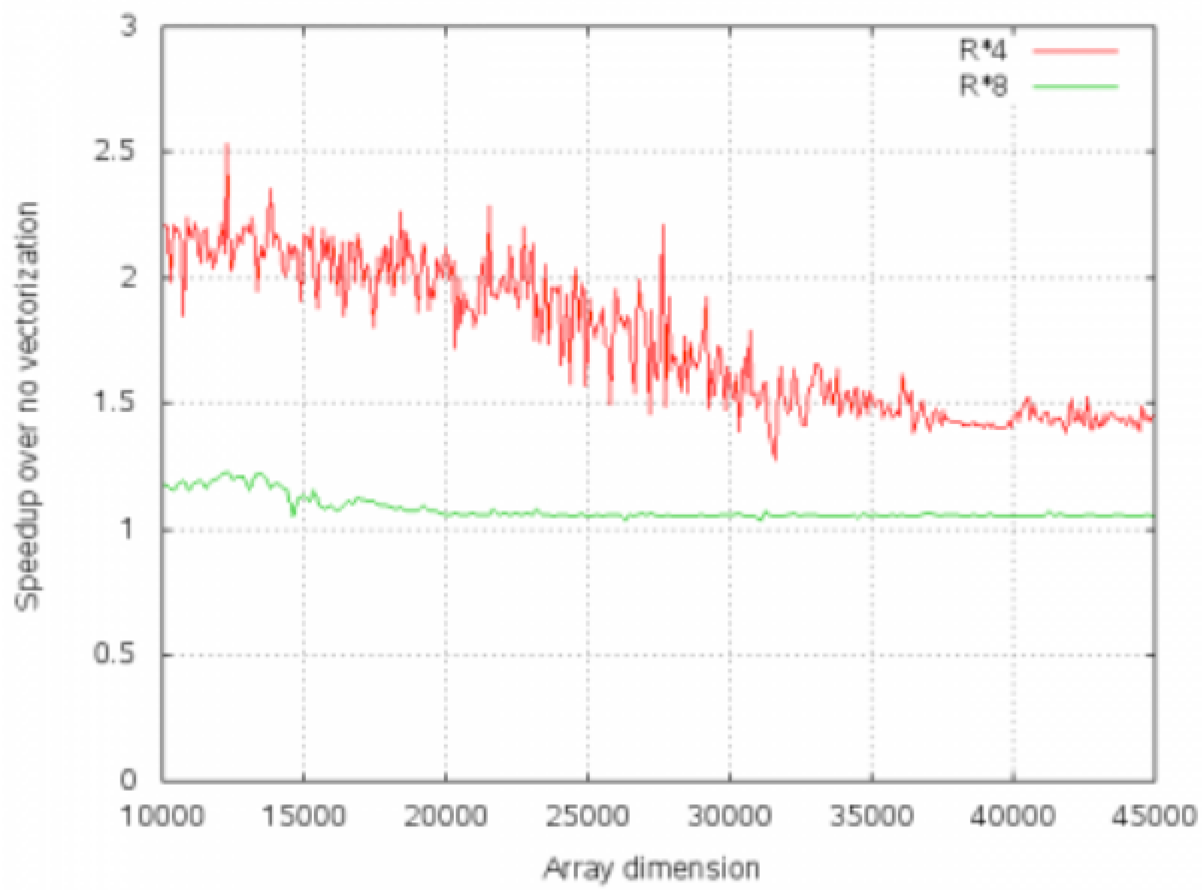
Что ожидать от производительности?

```
do i=1,n
    c(i) = a(i) + b(i)
end do
```



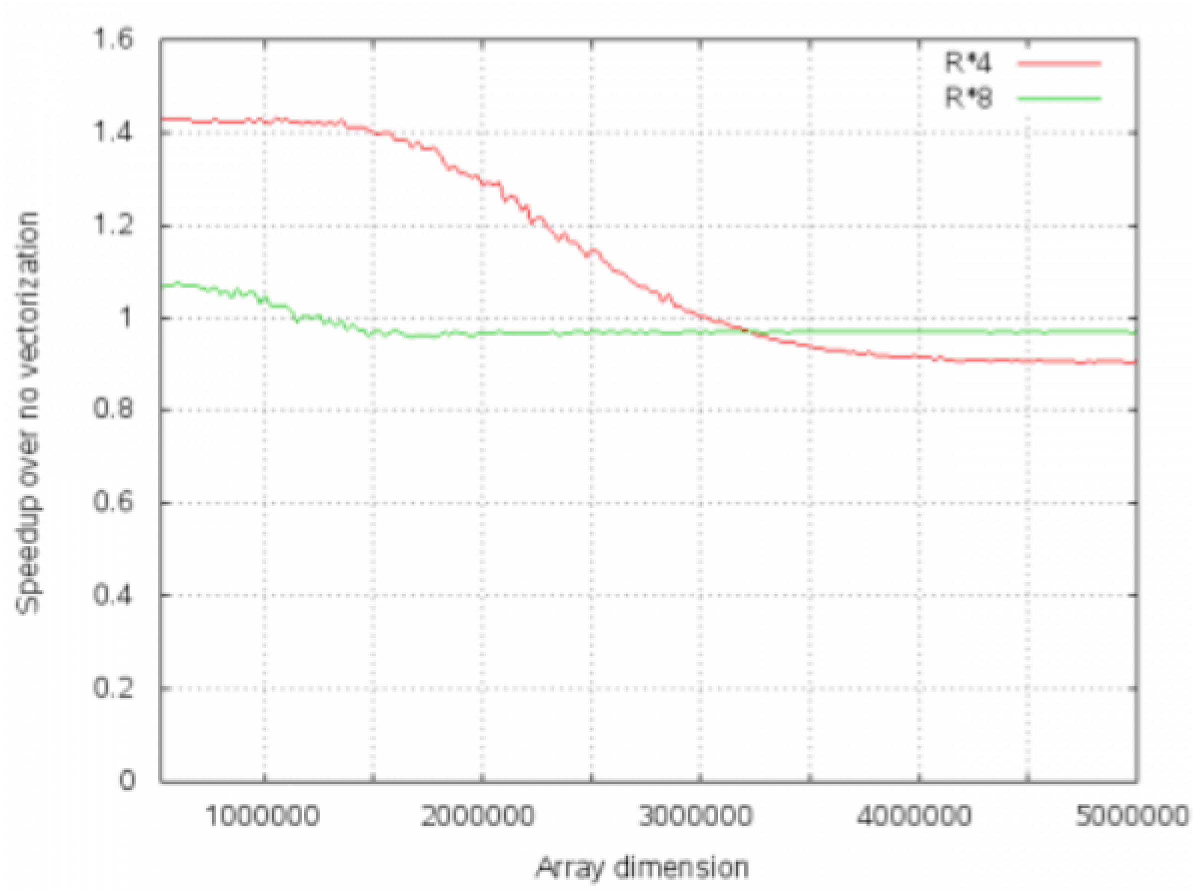
А дальше?

```
do i=1,n
    c(i) = a(i) + b(i)
end do
```



?

```
do i=1,n
    c(i) = a(i) + b(i)
end do
```



Блочная работа с СОЗУ

```
do i = 1, n
    do j = 1, m
        c += a(i) * b(j)
    enddo
enddo
```

Loads From DRAM:
n*m + n

```
do jout = 1, m, block
    do i = 1, n
        do j = jout, jout+block
            c += a(i) * b(j)
        enddo
    enddo
enddo
```

Loads From DRAM:
m/block * (n+block)
= **m*n/block** + m