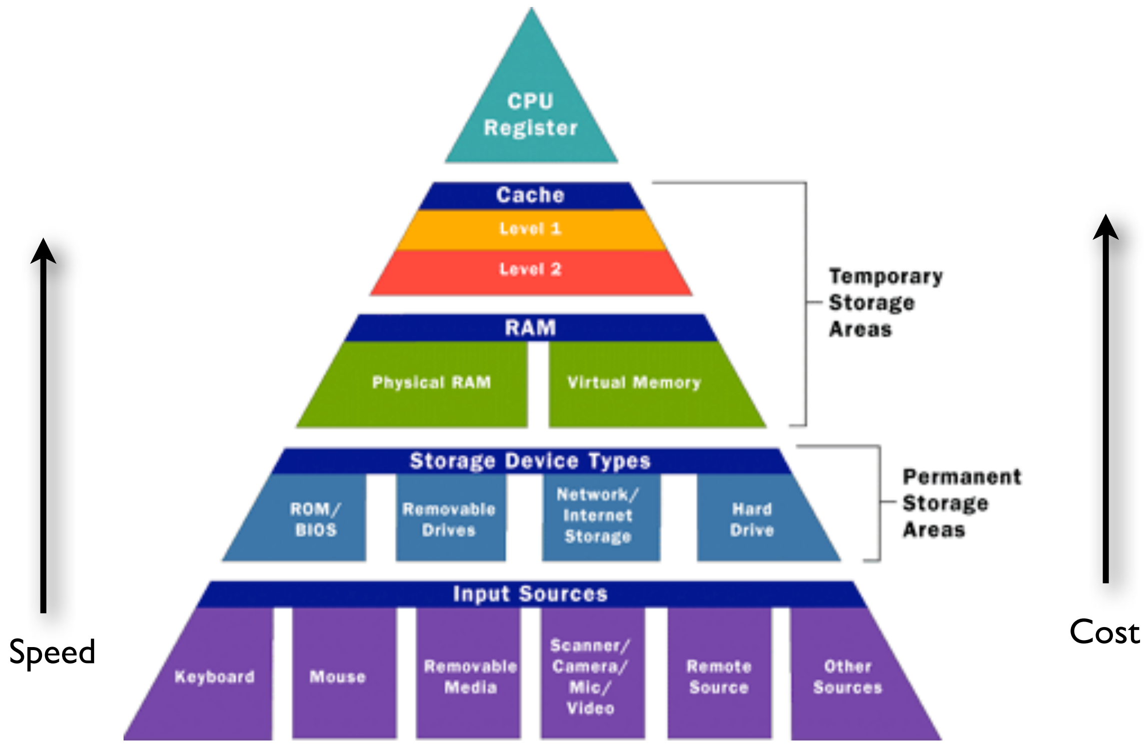
The Storage Hierarchy



Random Access Memory - RAM
(Main memory)

Bottleneck
(Slow)

RAM

CPU

CPU speed is much faster than the transfer speed between RAM and CPU; hence, if all data were only in RAM, the CPU would be idle most of the time

Cache

RAM

Bottleneck
(Slow)

Cache
Can have levels. L1, L2, L3
Each subsequent level is faster (but smaller - expensive!) than the previous

Fast

CPU

Cache/CPU speed is nearly the same as CPU speed;
Data should be continuously prefetched/pipelined to cache which then supplies CPU as needed.
Hence, the data flow between RAM/Cache/CPU should be predicted.
The instructions for the data flow are usually supplied by a compiler.
But you need to help it too!

Strategies for efficiency

- <u>Registers</u>: do maximum work at data already at registers before requesting new data
- <u>Cache</u>: maximum use of data already in cache; understand how data are stored in cache
- <u>Data locality</u>: priority access the data bits that already close to each other in memory before the bits that are far
- <u>Input/Output</u>: generally avoid at all costs; if must, do as much as possible at once rather than little bit at a time

Avoid Data Dependency

$$x = y+b$$
$$z = x+c$$

z depends on x

$$x = y+b$$
$$z = y+b+c$$

no dependency

Usually automatically done by a compiler when optimization is on

Avoid explicit integer power

```
x = y**3.0
```

expensive power-function may be called

```
x = y*y*y
```

Can be automatically done by a 'smart' compiler

Avoid divisions

$x = y / 2.$

devision can be much more expensive than multiplication

$$\downarrow$$

$x = 0.5*y$

Can be automatically done by a ‘smart’ compiler

Reduce computation of common subexpressions

```
x = y * (b / c)
z = f * (b / c)**2.5
```

↓

```
t = b / c
x = y * t
z = f * t**2.5
```

Can be automatically done by a 'smart' compiler

Watch out for Loop Invariants

```
do i=1,n
  x(i) = y(i) + z(i)*a/c(i)/b
  h(n) = f *a
end do
```

a/b does not depend on i

h(n) does not depend on i

↓

```
tmp = a/b
do i=1,n
  x(i) = y(i) + z(i)*tmp/c(i)
end do
h(n) = f *a
```

Look for conditions that dependent on loop index

```
do i=1,nx
 do j=1,ny
   if(x(j).gt.0) then
      y(i,j) = x(i) + z(i,j)*c(i)
   else
      y(i,j) = z(i,j)*b(i)
   end if
 end do
end do
```

Before

```
do j=1,ny
 if(x(j).gt.0) then
   do i=1,nx
       y(i,j) = x(i) + z(i,j)*c(i)
   end do
 else
   do i=1,nx
        y(i,j) = z(i,j)*b(i)
   end do
  end if
end do
```

After

Get boundary conditions outside the loop

```
do i=1,n
  if (i==1 .or. i==n) then
    x(i) = y(i)
  else
    x(i) = y(i)*d(i)
  end if
end do
```

Before

```
x(1) = y(1)
do i=1,nx
  x(i) = y(i)*d(i)
end do
x(n) = y(n)
```

After

Index Splitting

```
do i=1,n
  if (i<m) then
    x(i) = y(i)*c(i)
  else
    x(i) = y(i)*d(i)
  end if
end do
```

```
do i=1,m-1
  x(i) = y(i)*c(i)
end do
do i=m,n
  x(i) = y(i)*d(i)
end do
```

Before

After

Loop order exchange

Make 'slower' changing loop-index to be in outer loop,
fast index - inner loop

```
do i=1,nx
  do j =1,ny
    x(i,j) = y(i,j)+1
  end do
end do
```

Before

```
do j=1,ny
  do i =1,nx
    x(i,j) = y(i,j)+1
  end do
end do
```

After

In Fortran, array a(3,3) is stored as: a(1,1) a(2,1) a(3,1) a(1,2) a(2,2) a(3,2) a(1,3) a(2,3) a(3,3)

In C the order is reversed: a(1,1) a(1,2) a(1,3) a(2,1) a(2,2) a(2,3) a(3,1) a(3,2) a(3,3)

Loop fusion
(register reuse)

Only if all arrays in the loop fit in cache (small)

```
do i=1,n
   x(i) = y(i)+1
end do
do i=1,n
   a(i) = x(i)+c
end do
do i=1,n
   d(i) = a(i)+y(i)
end do
```

Before

```
do i=1,n
   x(i) = y(i)+1
   a(i) = x(i)+c
   d(i) = a(i)+y(i)
end do
```

After

Loop fission
(effective cache use)

Only if all arrays are large, so all don't fit in cache

```
do i=1,n
   x(i) = y(i)+1
   a(i) = x(i)+c
   d(i) = a(i)+y(i)
end do
```

Before

```
do i=1,n
   x(i) = y(i)+1
end do
do i=1,n
   a(i) = x(i)+c
end do
do i=1,n
   d(i) = a(i)+y(i)
end do
```

After

Avoid loop index dependencies

```
do i=1,n
   x(i) = x(i-1)*a(i)
   b(i) = x(i)*c(i)
end do
```

```
do i=0,n-1
   y(i) = x(i)*a(i+1)
end do
do i=1,n
   x(i) = y(i)*c(i)
end do
```

Before

After

avoid if's when can

```
if (x >= 1.) then
   x = 1.
elseif (x <=0.) then
   x = 0.
end if
```

```
x=min(1.,max(0.,x))
```

Before

After

avoid if's when can

```
if (u(i) >= 0.) then
   x(i) = u(i)*(x(i)-x(i-1))
else
   x(i) = u(i)*(x(i+1)-x(i))
end if
```

```
v=max(0.,u(i)) * (x(i)-x(i-1))+ &
   min(0.,u(i)) * (x(i+1)-x(i))
```

Before

After

Never call a subroutine/function within large loop

Before

```
do j=1,ny
 do i=1,nx
   ...
   y= fun(x(i,j))
 end do
end do

real function fun (x)
 x = x*cos(x)
end function fun
```

Inlining

After

```
do j=1,ny
 do i=1,nx
   ...
   y= x(i,j)*cos(x(i,j))
 end do
end do
```

Steps in code development:

Never call a subroutine/function within large loop

```
do j=1,ny
 do i=1,nx
   ...
   call micro()
   ...
 end do
end do
```

Before

```
subroutine micro()
...
do j=1,ny
 do i=1,nx
   ...
 end do
end do
...
end subroutine micro
```

After

Some advise

- new code should go through initial test compiling with optimization off, unitialized memory and array bound checks on;
- If the program fails after ported to another system or after not using the code for awhile, try running first with optimization off;
- Always try to use maximum compiler optimization; but make sure the results are similar (not the same) with lower optimization
- Use comments, sensible names for variables, indenting;
- One file per subroutine/module;
- Never use ‘magic numbers’.