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Exécuter un programme en parallèle sur un processeur Many-core

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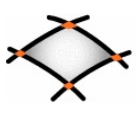
DALI, équipe-projet du LIRMM



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Digits, Architectures et Logiciels Informatiques

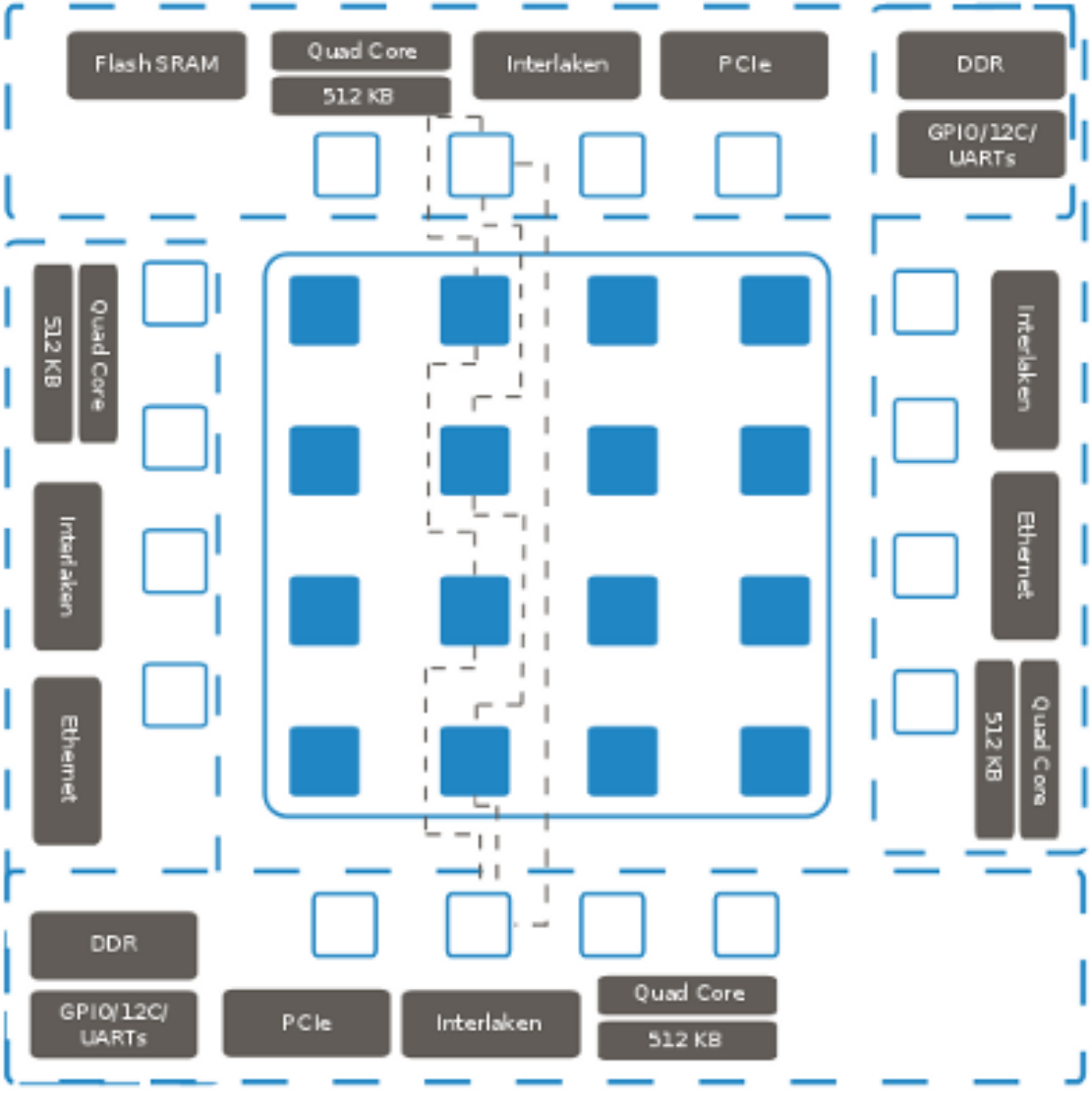
LIRMM

Plan de la présentation.

Un algorithme parallèle : la réduction de somme.

```
sum_reduce(t[0..n[) :
 if n=2 then t[0] + t[1]
 else sum_reduce(t[0..n/2[) + sum_reduce(t[n/2..n[)
```

Un processeur Many-core : le MPPA-256 de Kalray.



Comment exécuter un algorithme en parallèle sur un Many-core ?

- Implémentation pthread, MPI ...

Comment exécuter un algorithme en parallèle sur un Many-core ?

- Implémentation pthread, MPI ...
- Utiliser une bibliothèque de l'OS pour implémenter la distribution, la communication et la synchronisation.

Une implémentation Pthread.

```
typedef struct{int *t; int n;} ST;
void *sum_reduce(void *st){
 unsigned int s,s1,s2;
 ST str1,str2;
 pthread_t tid1, tid2;
 if (((ST *)st)->n==2){
  return ((ST *)st)->t[0] + ((ST *)st)->t[1];
 }
 str1.t=((ST *)st)->t; str1.n=((ST *)st)->n/2;
 pthread_create(&tid1,NULL,sum_reduce,(void *)&str1);
 str2.t=((ST *)st)->t + ((ST *)st)->n/2; str2.n=((ST *)st)->n/2;
 pthread_create(&tid2,NULL,sum_reduce,(void *)&str2);
 pthread_join(tid1,(void *)&s1); pthread_join(tid2,(void *)&s2);
 s=s1+s2; pthread_exit((void *)s);
}
```

Une implémentation MPI.

```
#include "mpi.h"
...
//i: local data element; s: recv, update (sum) and send s;
MPI_Reduce(&i, &s, 1, MPI_INT, MPI_SUM, 0, MPI_COMM_WORLD);
...
```

Une implémentation pour GPU en CUDA.

```
__global__ void sum_reduce(int *t, int *sum){
 int tid = threadIdx.x;
 extern __shared__ s_data[];
 //to load the data from global memory to warp local shared memory
 s_data[tid] = ...;
 __syncthreads();
 for (int i=s_data_sizel; i>0; i/=2){
   if (tid < i){
     s_data[tid] = s_data[tid] + s_data[i+tid];
     __syncthreads();
   }
 }
 if (tid==0) sum[0]=s_data[0];
}
```

Une implémentation en C.

```
(0) unsigned int sum_reduce(unsigned int t[], unsigned int n){
(1)   if (n==2)
(2)     return t[0]+t[1];
(3)   else
(7)     return
(4)       sum_reduce(t,n/2)
(6)     +
(5)       sum_reduce(&t[n/2],n/2);
(8) }
```

Exécution du code C.

```
sum_reduce(&t[0], 8) =
  (1) (3) (4)
          sum_reduce(&t[0],4)
            (1) (3) (4)
                    sum_reduce(&t[0],2)
                      (1) (2)
            (5)
                    sum_reduce(&t[2],2)
                      (1) (2)
            (6) (7)
  (5)
          sum_reduce(&t[4],4)
            (1) (3) (4)
                    sum_reduce(&t[4],2)
                      (1) (2)
            (5)
                    sum_reduce(&t[6],2)
                      (1) (2)
            (6) (7)
  (6) (7)

trace = (1) (3) (4) (1) (3) (4) (1) (2) (5)
        (1) (2) (6) (7) (5) (1) (3) (4) (1)
        (2) (5) (1) (2) (6) (7) (6) (7)
```

Qu'est-ce qui séquentialise l'implémentation C ?

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- Ce n'est pas le code C.
- C'est le modèle d'exécution employé : le modèle de Von Neumann.
- Ce modèle suppose l'existence d'un pointeur d'instruction IP contrôlant la phase d'extraction du programme enregistré en mémoire.

Traduction du code C pour une architecture Von Neumann.

```
(01) sum_reduce:   pushq %rbx                    #save t
(02)               pushq %rbp                    #save n
(03)               subq  $8, %rsp                #allocate tmp
(04)               cmpq  $2, %rbp                #if (n!=2)
(05)               jne   .L2                     #goto .L2
(06)               movq  8(%rbx), %rax           #a=t[1]
(07)               addq  (%rbx), %rax            #a+=t[0]
(08)               jmp   .L3                     #goto .L3
(09) .L2:          shrq  %rbp                    #n=n/2
(10)               call  sum_reduce              #a=sum(t,n/2)
(11)               movq  %rax, 0(%rsp)           #tmp=a
(12)               leaq  (%rbx,%rbp,8), %rbx     #t=&t[n/2]
(13)               call  sum_reduce              #a=sum(&t[n/2],n/2)
(14)               addq  0(%rsp), %rax           #a+=tmp
(15) .L3:          addq  $8, %rsp                #free tmp
(16)               popq  %rbp                    #restore n
(17)               popq  %rbx                    #restore t
(18)               ret                           #return a
```

Exécution du code assembleur.

```
sum_reduce(&t[0], 8) =
 7  (01)-(05), (09), (10)
          sum_reduce(&t[0],4)
 7            (01)-(05), (09), (10)
                    sum_reduce(&t[0],2)
12                        (01)-(08), (15)-(18)
 3            (11)-(13)
                    sum_reduce(&t[2],2)
12                        (01)-(08), (15)-(18)
 5            (14)-(18)
 3  (11)-(13)
          sum_reduce(&t[4],4)
 7            (01)-(05), (09), (10)
                    sum_reduce(&t[0],2)
12                        (01)-(08), (15)-(18)
            (11)-(13)
                    sum_reduce(&t[2],2)
12                        (01)-(08), (15)-(18)
 5            (14)-(18)
 5  (14)-(18)
90

trace = 90 instructions
```

Le parallélisme d'instruction ou ILP.

- ILP proche du pointeur d'instruction (centaines d'instructions).

Le parallélisme d'instruction ou ILP.

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- ILP distant, c-à-d K ou M ou G instructions.

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- Vraies dépendances : producteur -> consommateur (données et contrôle).
- Fausses dépendances : ressources (registres et mémoire).

Vraies dépendances sur l'exemple.

```
(01) sum_reduce:   pushq %rbx                  # prod %rbx
(02)               pushq %rbp                  # 01, prod %rbp
(03)               subq  $8, %rsp              # 02
(04)               cmpq  $2, %rbp              # prod %rbp
(05)               jne   .L2                   # 04
(06)               movq  8(%rbx), %rax         # 05, prod %rbx, prod (%rbx)
(07)               addq  (%rbx), %rax          # 05, 06, prod %rbx, prod (%rbx
(08)               jmp   .L3                   # 05
(09) .L2:          shrq  %rbp                  # 05, prod %rbp
(10)               call  sum_reduce            # 05, 02
(11)               movq  %rax, 0(%rsp)         # 05, prod (%rsp), prod %rax
(12)               leaq  (%rbx,%rbp,8), %rbx   # 05, prod %rbx, prod %rbp
(13)               call  sum_reduce            # 05, prod %rsp
(14)               addq  0(%rsp), %rax         # 05, prod %rsp, prod (%rsp)
(15) .L3:          addq  $8, %rsp              # 02
(16)               popq  %rbp                  # 15, 02
(17)               popq  %rbx                  # 16, 01
(18)               ret                         # 17, prod (%rsp)
```

Fausses dépendances sur l'exemple.

```
(01) sum_reduce:   pushq %rbx                  # ecr en (%rsp), lec en (%rsp)
(02)               pushq %rbp                  # ecr en (%rsp), lec en (%rsp)
(03)               subq  $8, %rsp              # 02
(04)               cmpq  $2, %rbp              # ecr en %eflags, lec en %eflag
(05)               jne   .L2                   #
(06)               movq  8(%rbx), %rax         # ecr en %rax, lec en %rax
(07)               addq  (%rbx), %rax          # 06
(08)               jmp   .L3                   #
(09) .L2:          shrq  %rbp                  # ecr en %rbp, lec en %rbp
(10)               call  sum_reduce            # ecr en %rsp, lec en %rsp
(11)               movq  %rax, 0(%rsp)         # ecr en (%rsp), lec en (%rsp)
(12)               leaq  (%rbx,%rbp,8), %rbx   # ecr en %rbx, lec en %rbx
(13)               call  sum_reduce            # ecr en %rsp, lec en %rsp
(14)               addq  0(%rsp), %rax         # ecr en %rax, lec en %rax
(15) .L3:          addq  $8, %rsp              # ecr en %rsp, lec en %rsp
(16)               popq  %rbp                  # ecr en %rbp, lec en %rbp
(17)               popq  %rbx                  # ecr en %rbx, lec en %rbx
(18)               ret                         #
```

La duplication de l'espace par le renommage. Dépendances EAL.

```
v3 = v1 op1 v2
v1 = v4 op2 v5
```

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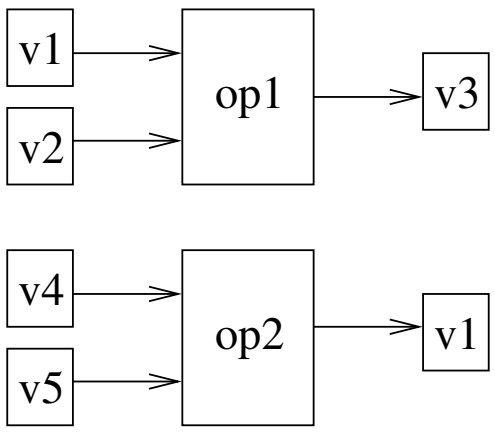

Sans renommage: 2 séquences

La duplication de l'espace par le renommage. Dépendances EAL.

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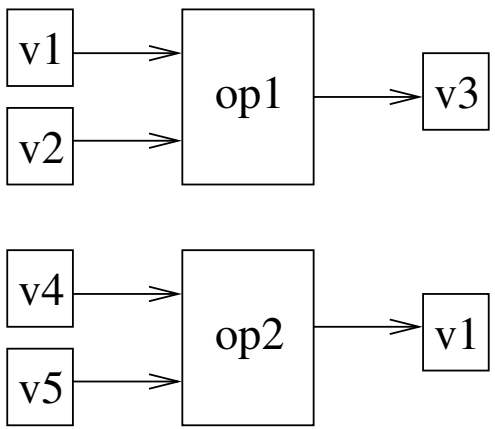

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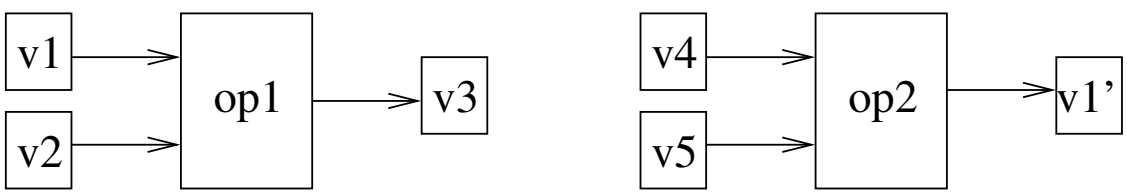

Avec renommage v1–>v1': 1 séquence

La duplication de l'espace par le renommage. Dépendances EAE.

```
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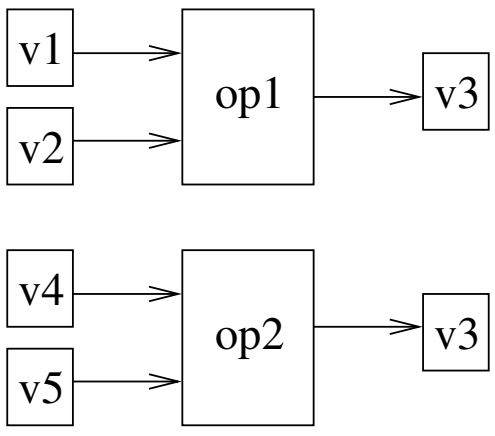

Sans renommage: 2 séquences

La duplication de l'espace par le renommage. Dépendances EAE.

```
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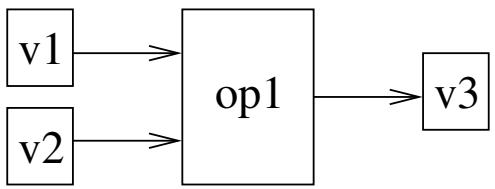
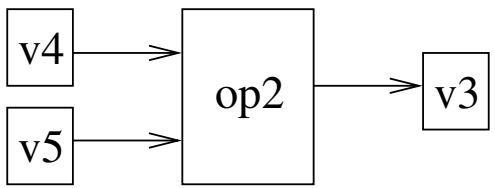
v3 = v4 op2 v5
```





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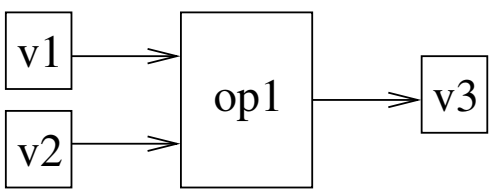

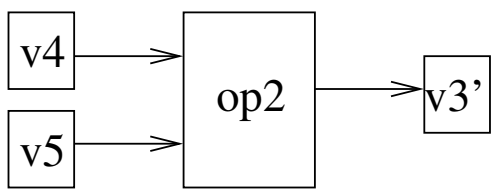

Avec renommage v3–>v3': 1 séquence

La spéculation de la source (IP) par la prédiction de saut. Dépendances de contrôle.

```
        jne .L1
.L1     v3 = v1 op v2
```

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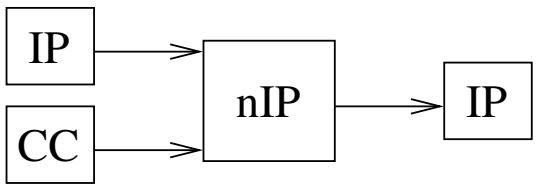

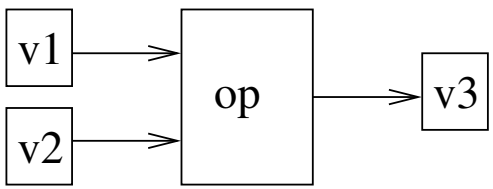

Sans prédiction: 2 séquences

La spéculation de la source (IP) par la prédiction de saut. Dépendances de contrôle.

```
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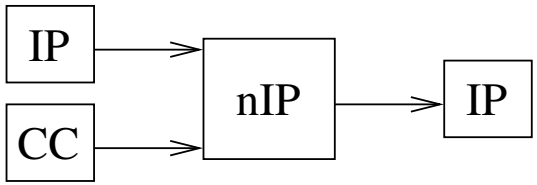
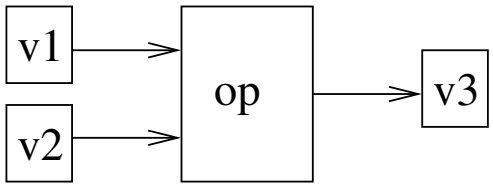
.L1     v3 = v1 op v2
```





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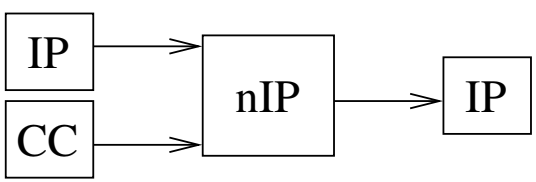
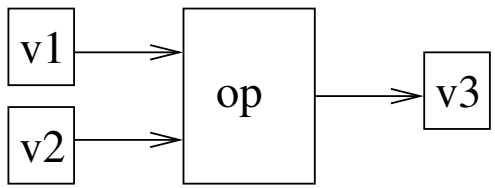


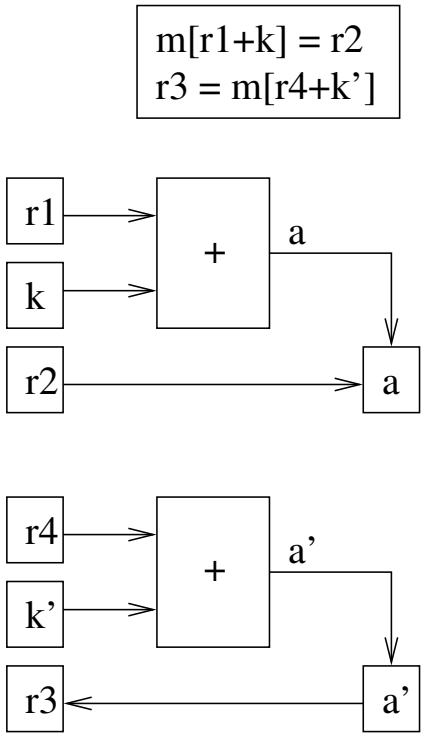


Avec prédiction: 1 séquence

La spéculation de la source par son chargement anticipé. Dépendances de mémoire.

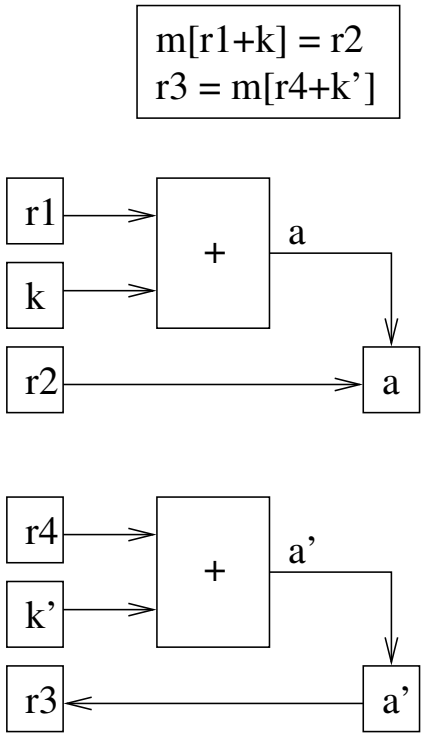
```
m[r1+k] = r2
r3 = m[r4+k']
```

La spéculation de la source par son chargement anticipé. Dépendances de mémoire.



Sans spéculation: 2 séquences

La spéculation de la source par son chargement anticipé. Dépendances de mémoire.



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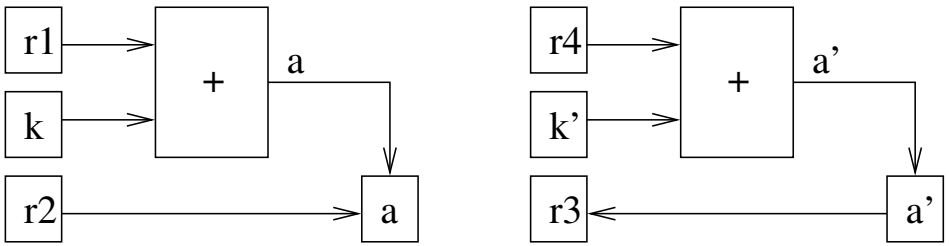
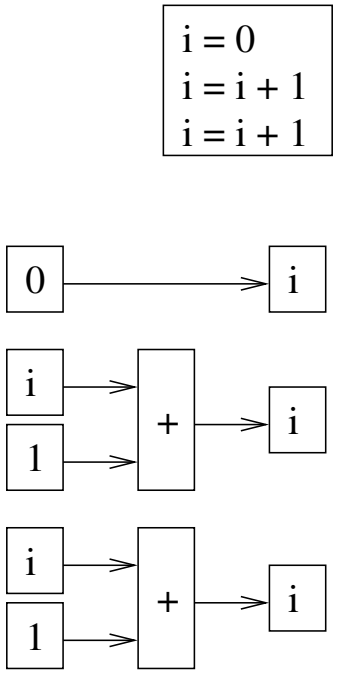


Avec spéculation: 1 séquence

Le calcul au renommage. Dépendances de données.

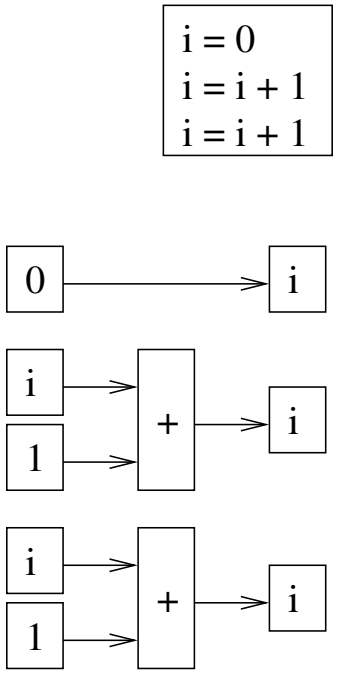
```
i = 0
i = i + 1
i = i + 1
```

Le calcul au renommage. Dépendances de données.



Sans précalcul: 3 séquences

Le calcul au renommage. Dépendances de données.



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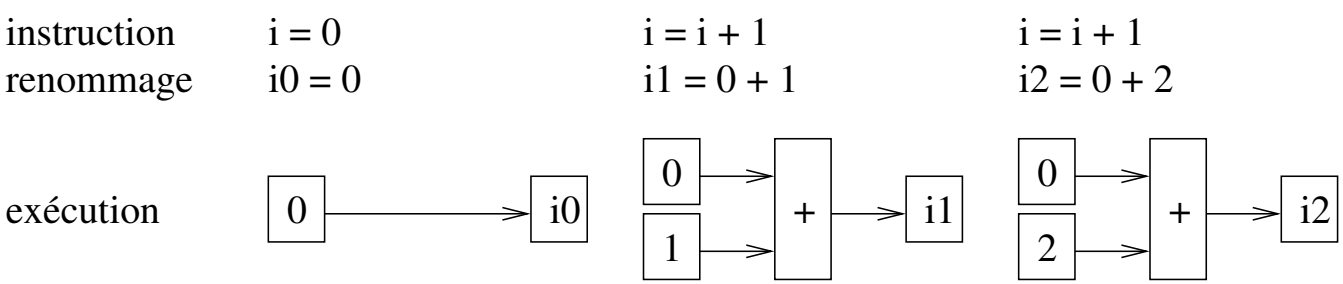

Avec précalcul: 1 séquence

Le partage de l'espace et l'élimination des copies. Dépendances de données.

```
mov v1, v2
mov v2, v3
mov v3, v4
```

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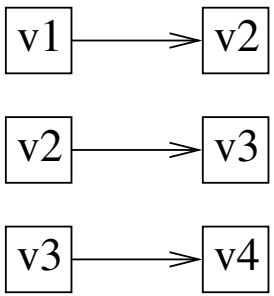

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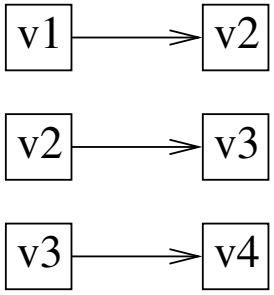

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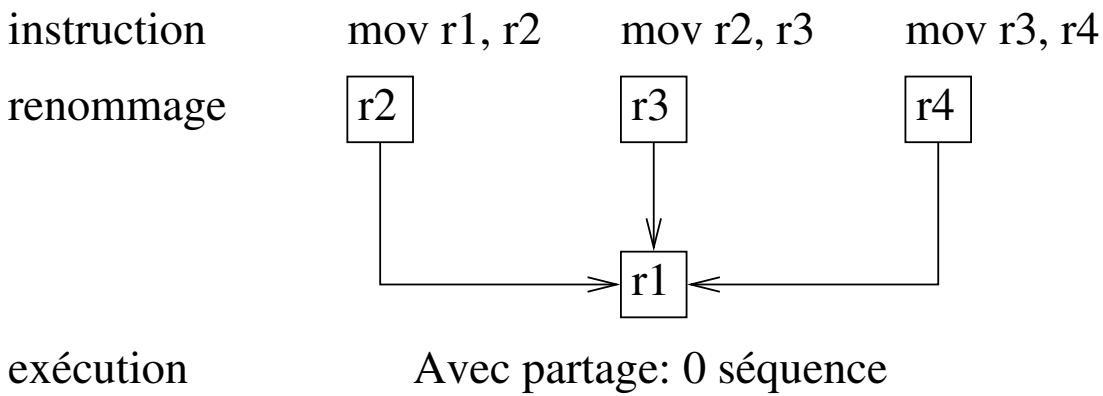
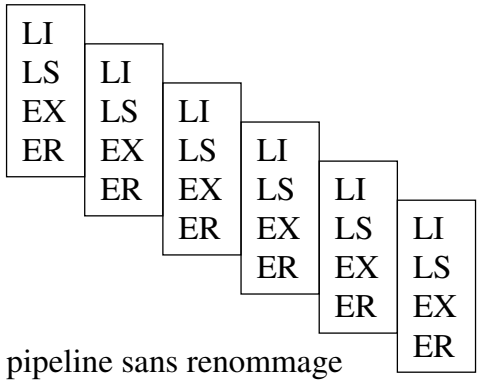


Une phase de renommage.

lecture d'une instruction
lecture de ses sources
exécution
écriture de ses résultats



pipeline sans renommage

Une phase de renommage.

lecture d'une instruction
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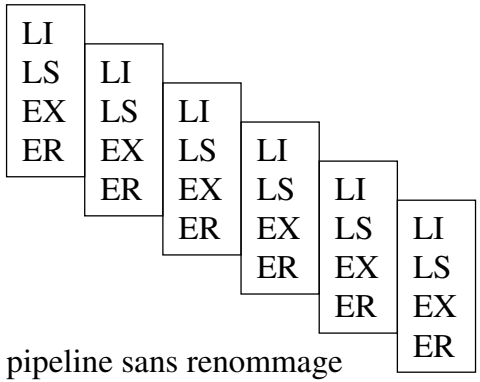
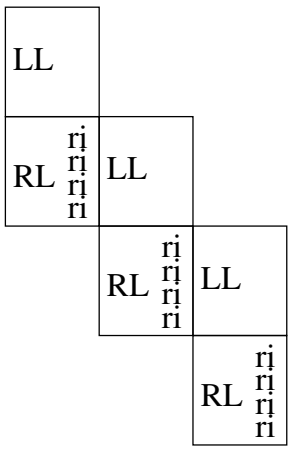


pipeline sans renommage

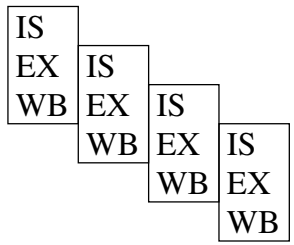
lecture d'une ligne d'instructions

renommage d'une instruction



pipeline de renommage

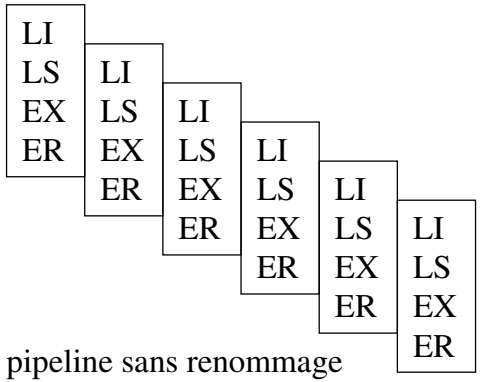
démarrage ooo des instructions prêtes
exécution en parallèle
terminaison



pipeline d'exécution ooo

Une phase de renommage.

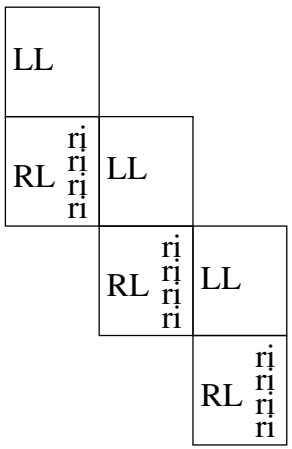
lecture d'une instruction
lecture de ses sources
exécution
écriture de ses résultats



pipeline sans renommage

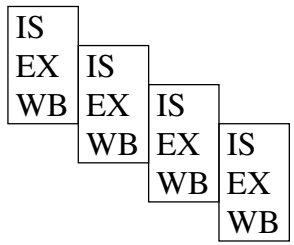
lecture d'une ligne d'instructions

renommage d'une instruction

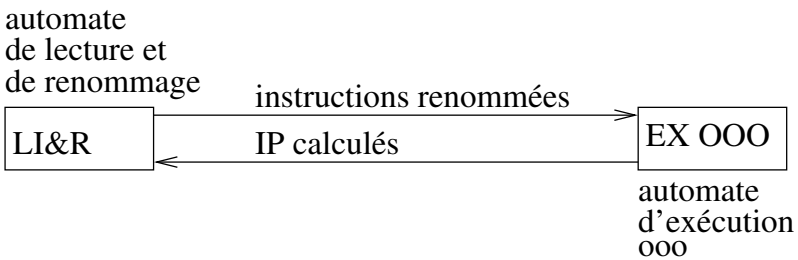


pipeline de renommage

démarrage ooo des instructions prêtes
exécution en parallèle
terminaison



pipeline d'exécution ooo



Un prédicteur de saut.

- Prédit les sauts conditionnels (direction et cible).

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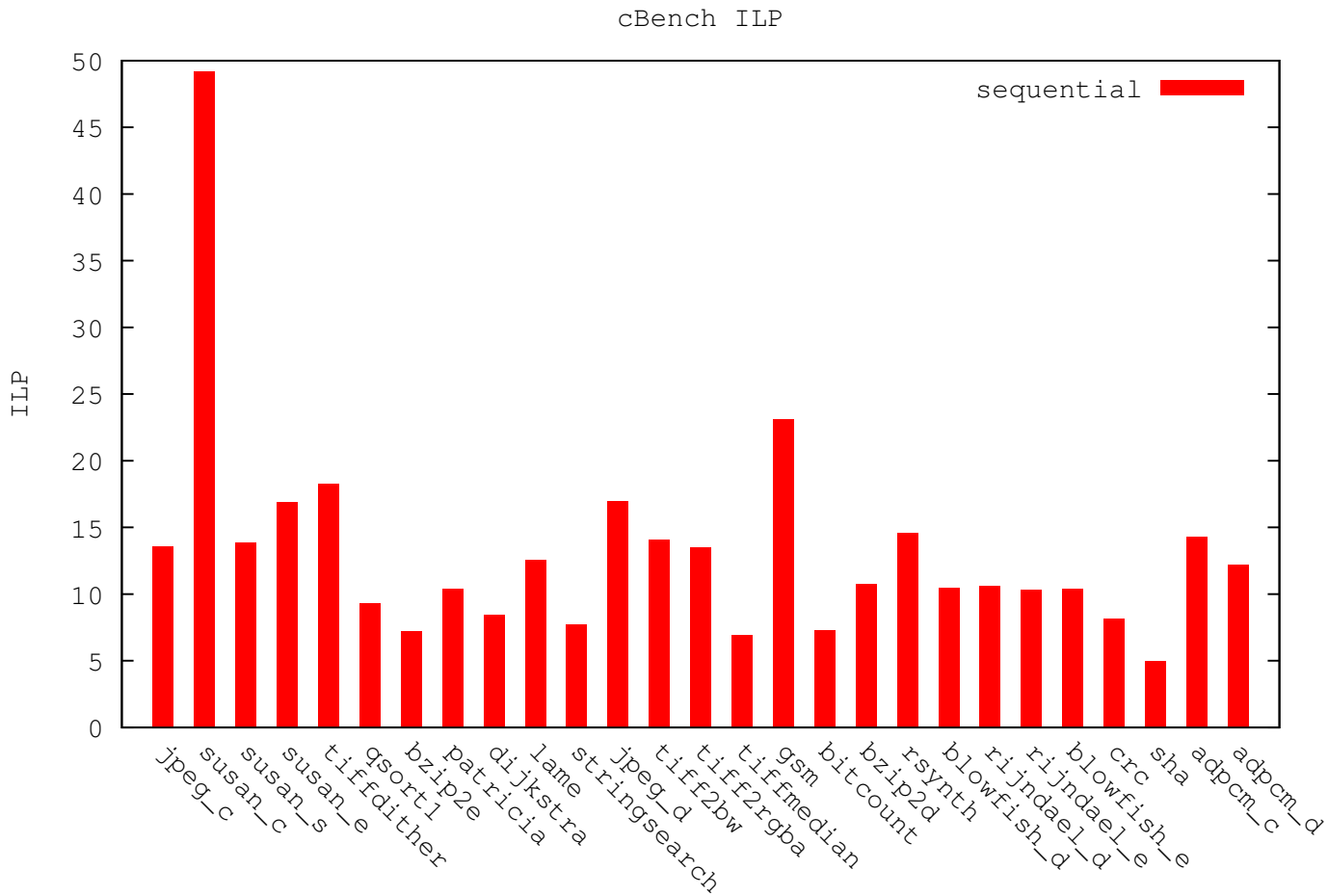
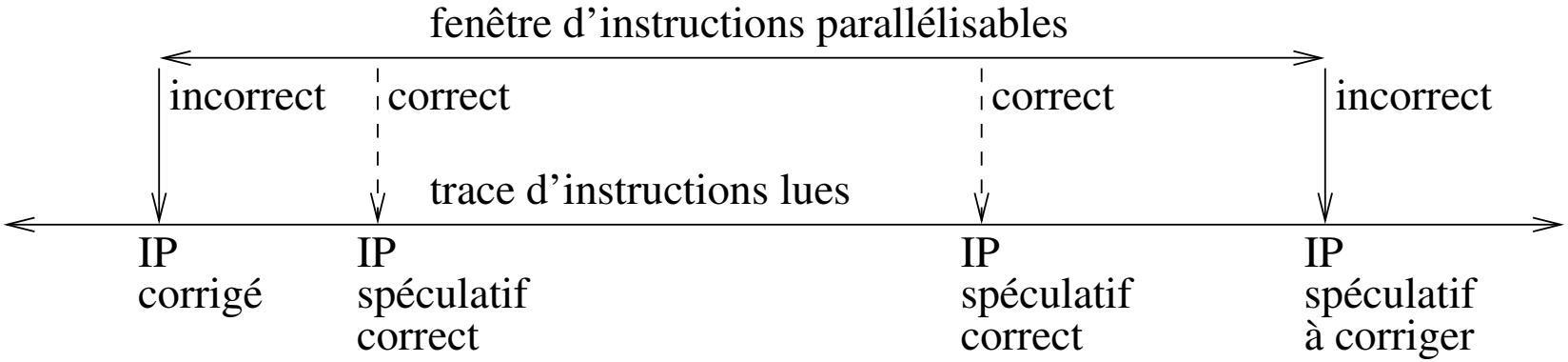
- Prédit les sauts conditionnels (direction et cible).
- Prédit les sauts inconditionnels indirects (cible).
- Prédit les retours de fonction.
- Taux de succès : 97%.

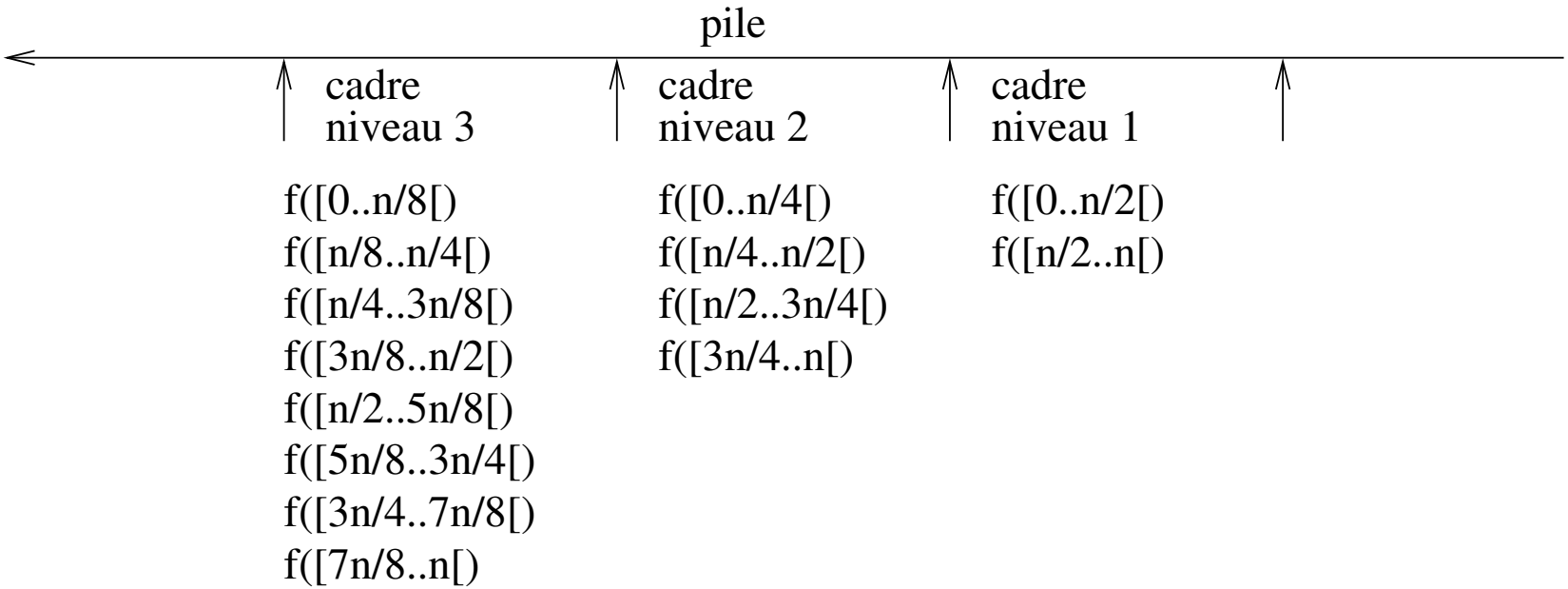
Impact de la parallélisation par le renommage mémoire et la prédiction de saut.



Premier verrou : séquentialisation par le contrôle.



Second verrou : séquentialisation par la gestion de la pile.



Comment lever le verrou sur le contrôle ?

- On ne sait pas prédire une trace au delà de quelques centaines d'instructions mais

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- Le point de retour d'un appel de fonction.

Comment lever le verrou sur le contrôle ?

- On ne sait pas prédire une trace au delà de quelques centaines d'instructions mais

  on en connaît des points de passage sûrs tout au long du parcours.

- Le point de retour d'un appel de fonction.
- La sortie d'une boucle.

Comment lever le verrou sur la pile ?

- On ne sait pas positionner le cadre d'un appel de fonction dans la pile sans avoir positionné le cadre de la fonction appelante mais

Comment lever le verrou sur la pile ?

- On ne sait pas positionner le cadre d'un appel de fonction dans la pile sans avoir positionné le cadre de la fonction appelante mais

  la position du pointeur de pile au retour est la même qu'à l'appel.

Comment lever le verrou sur la pile ?

- On ne sait pas positionner le cadre d'un appel de fonction dans la pile sans avoir positionné le cadre de la fonction appelante mais

  la position du pointeur de pile au retour est la même qu'à l'appel.

- Spéculer sur la position du pointeur de pile.

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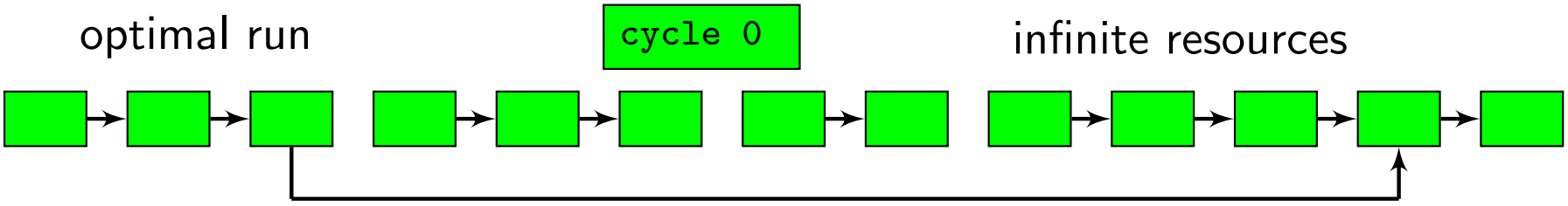
  la position du pointeur de pile au retour est la même qu'à l'appel.

- Spéculer sur la position du pointeur de pile.
- Distinguer les cadres d'appels de même niveau par renommage.

How to capture distant ILP.



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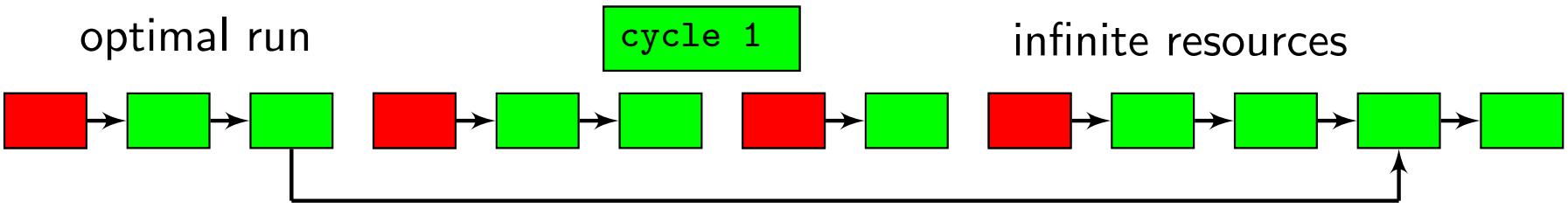

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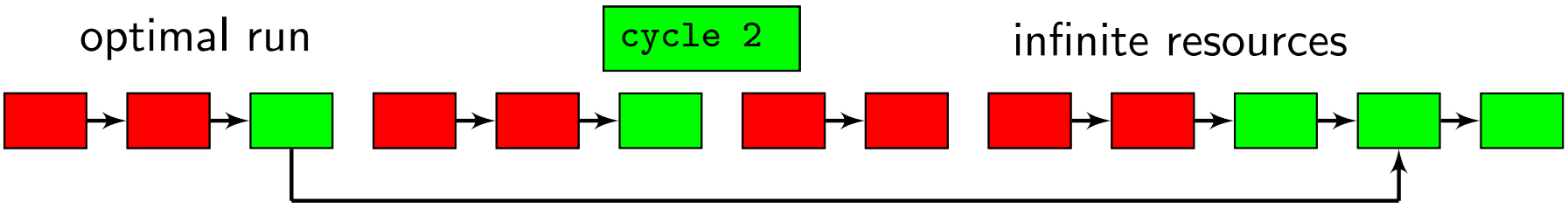

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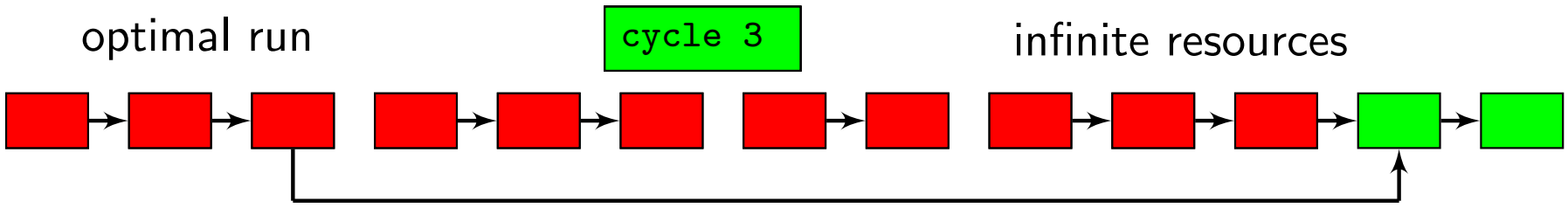

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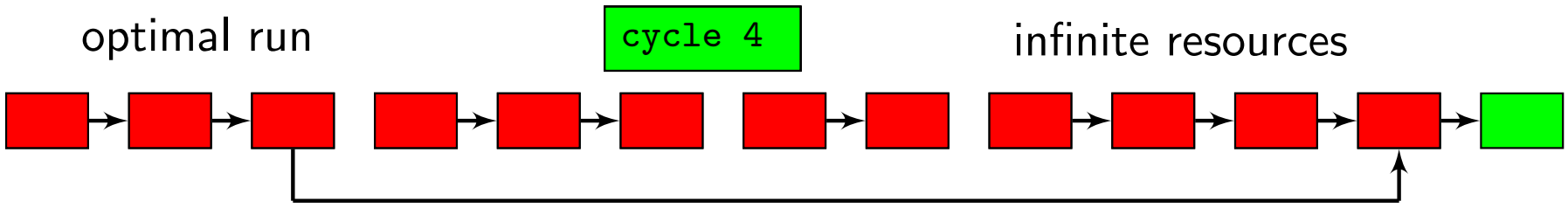

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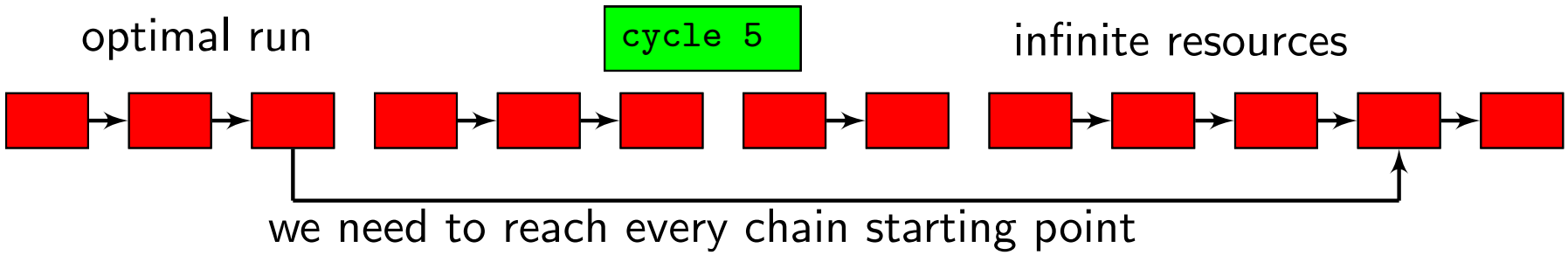

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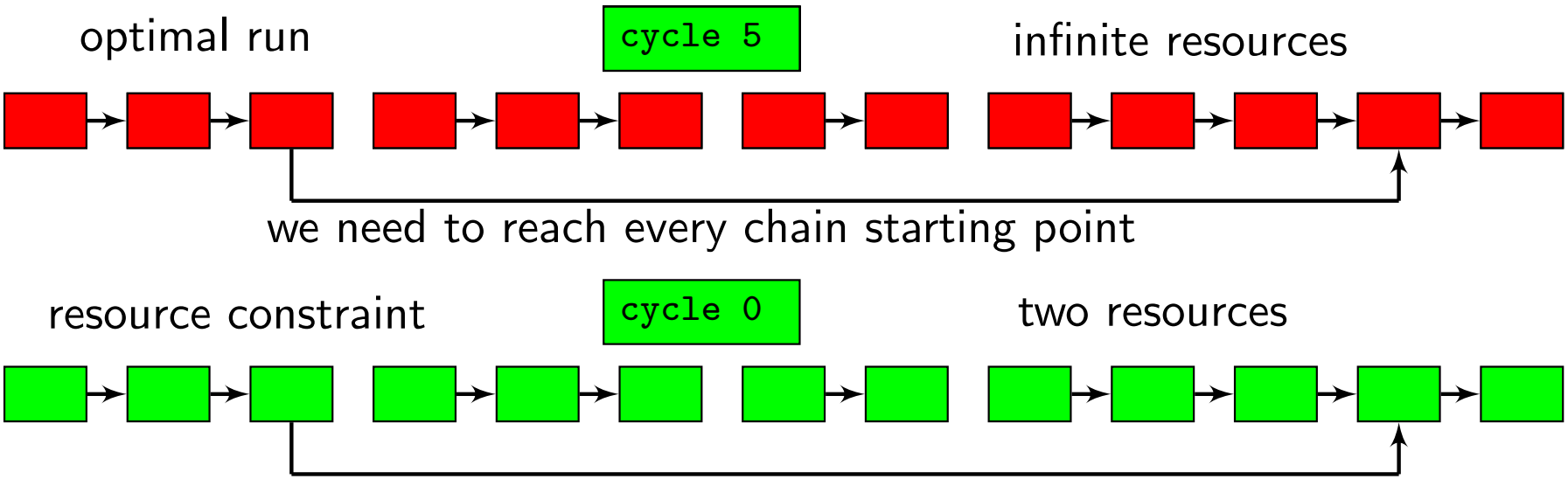

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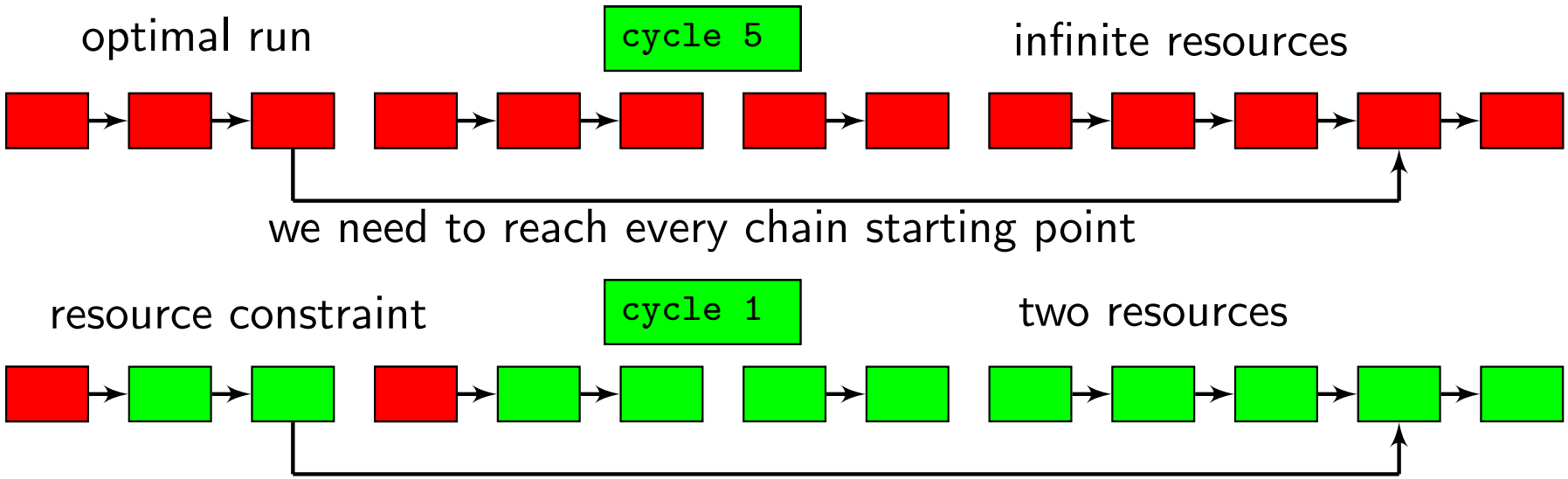

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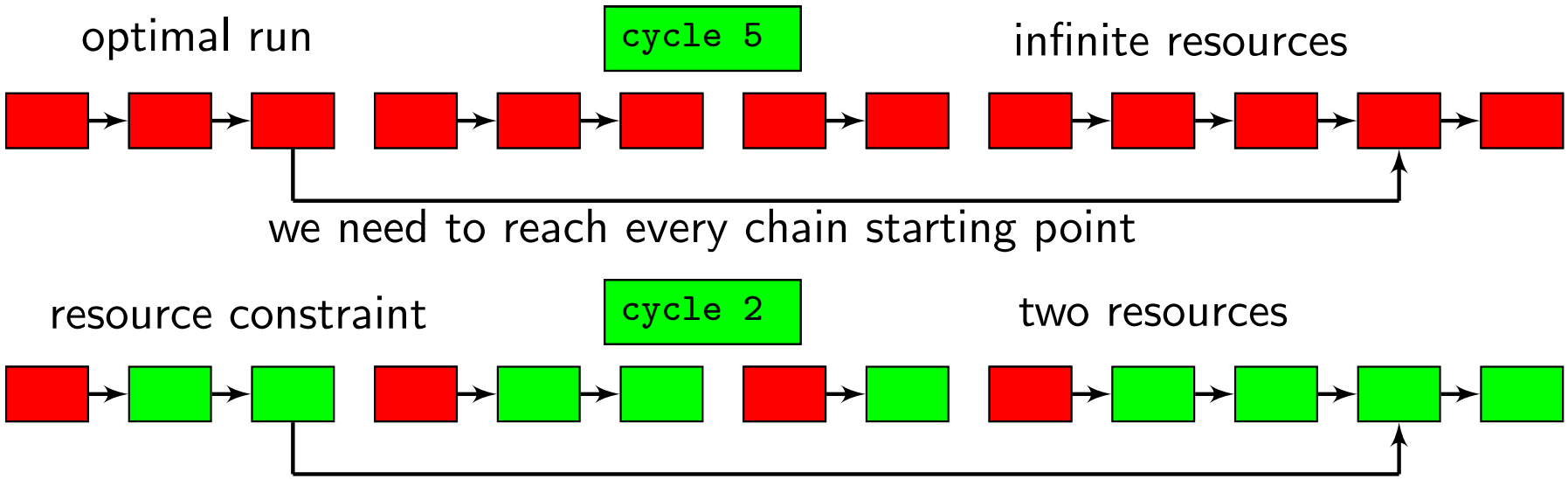

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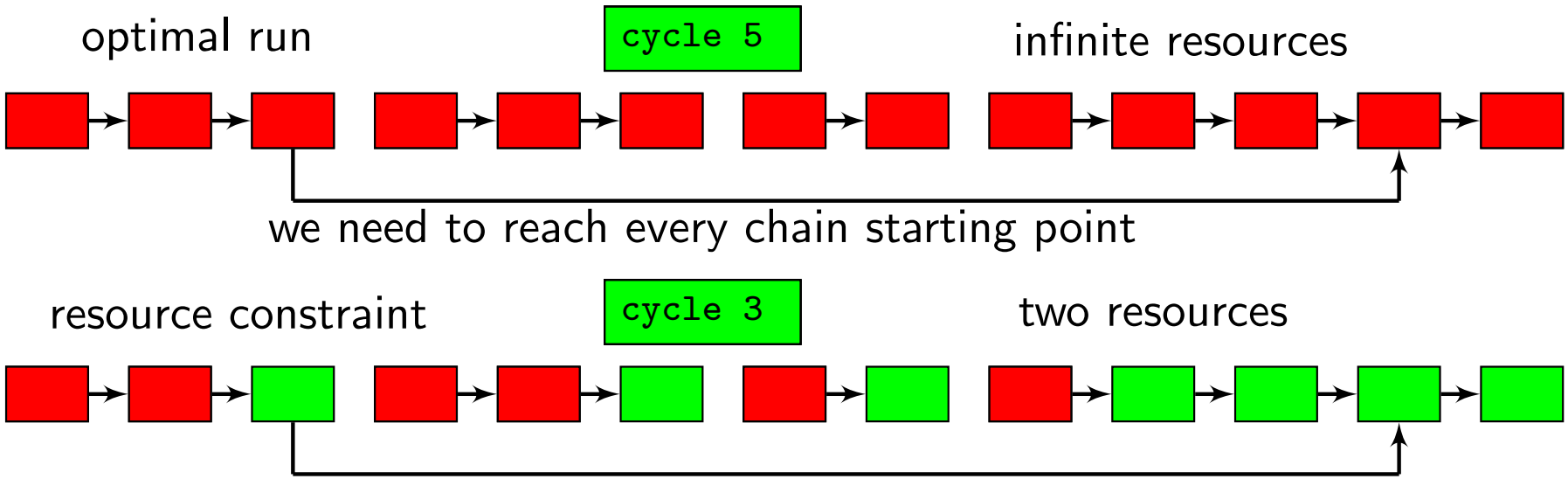

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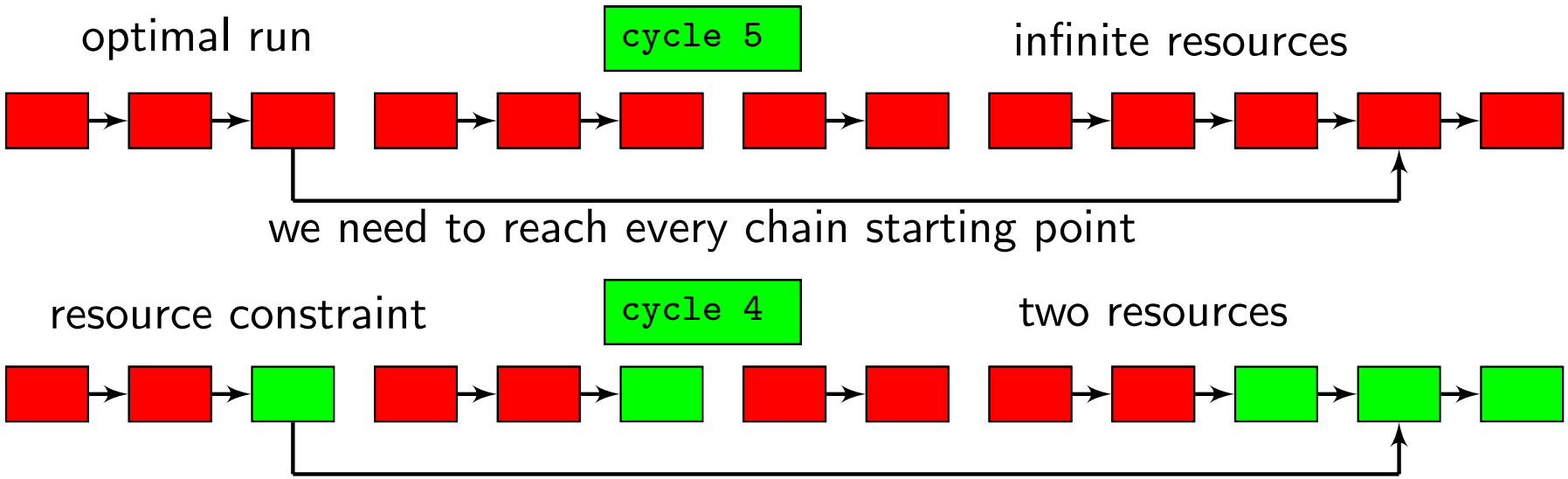

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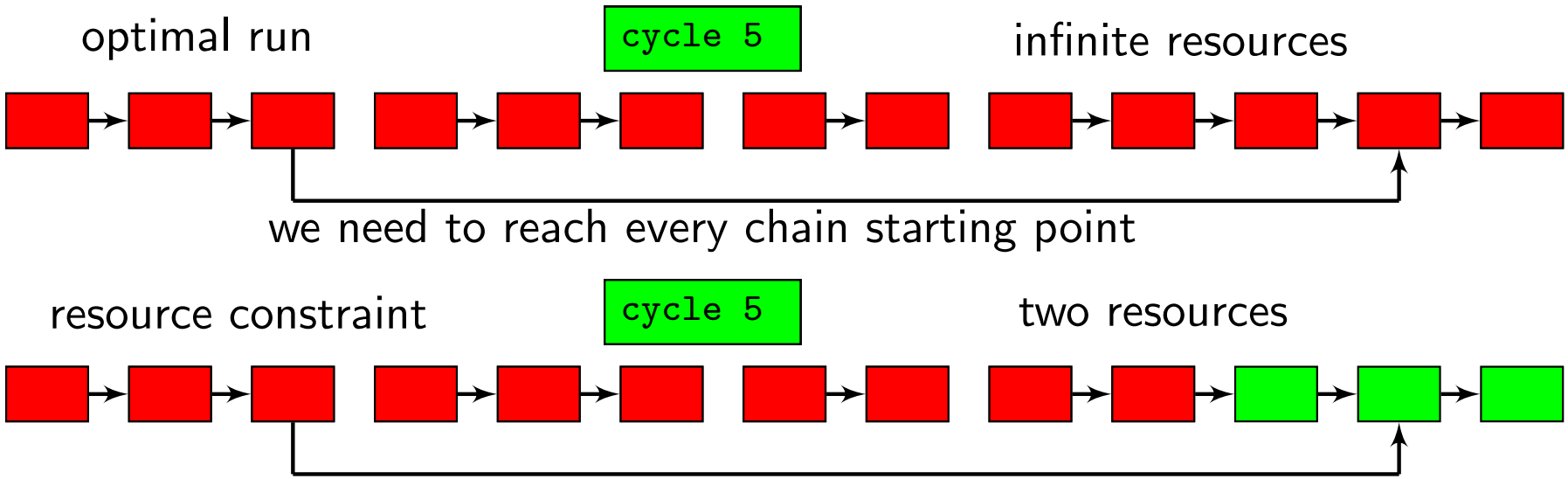

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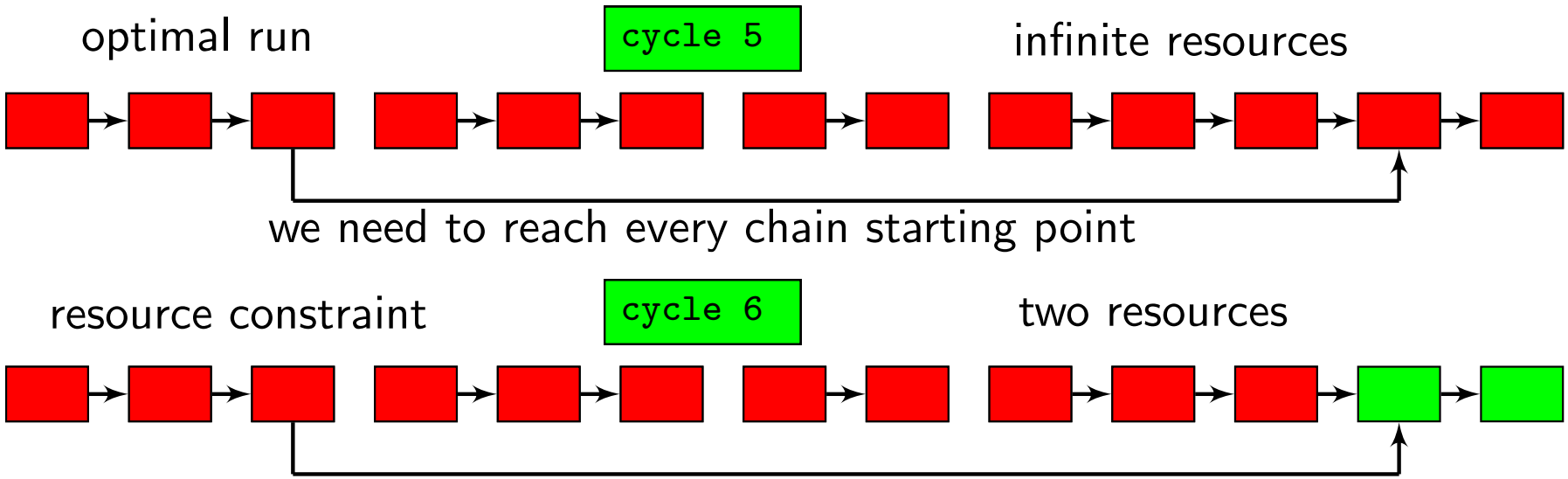

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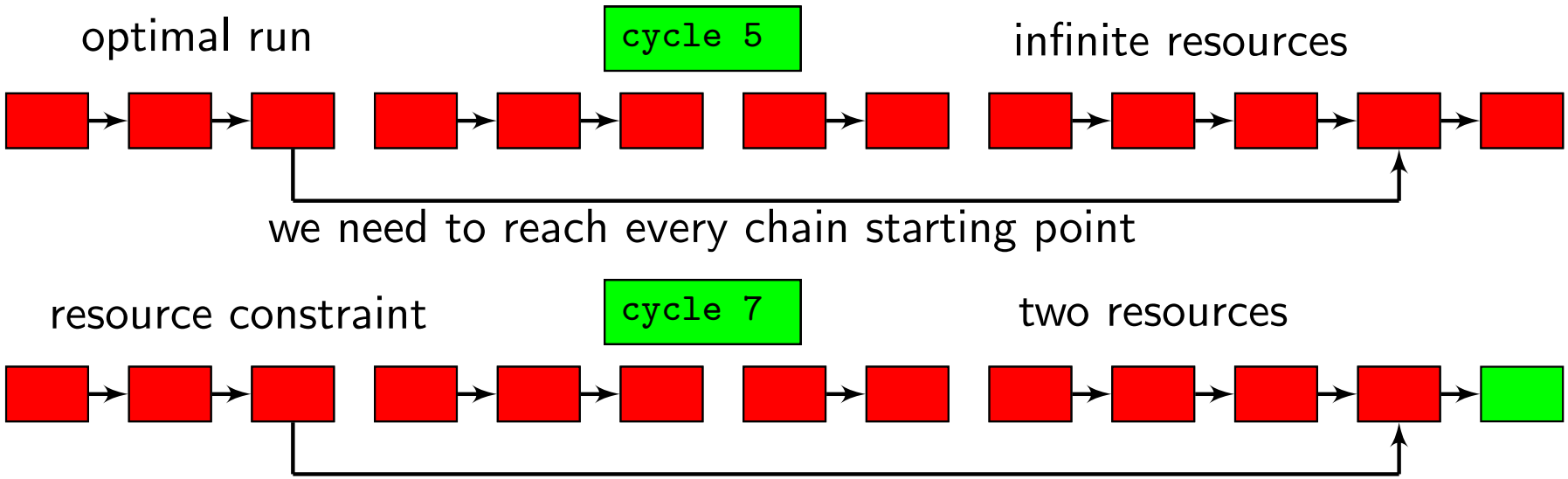

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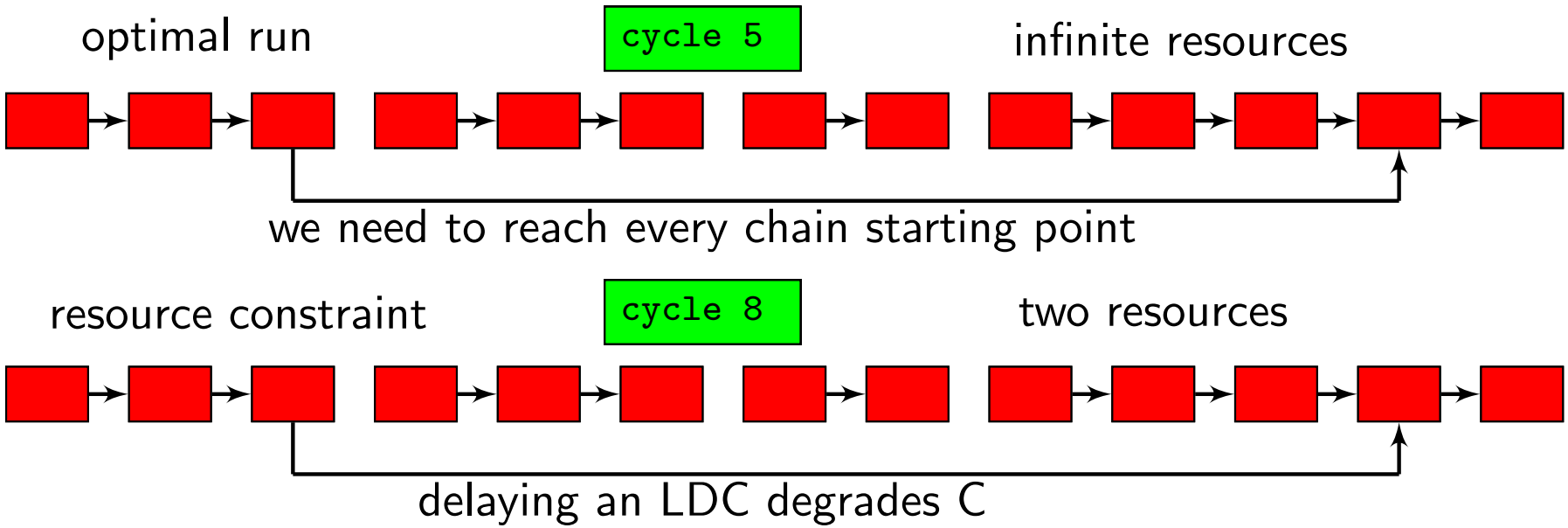

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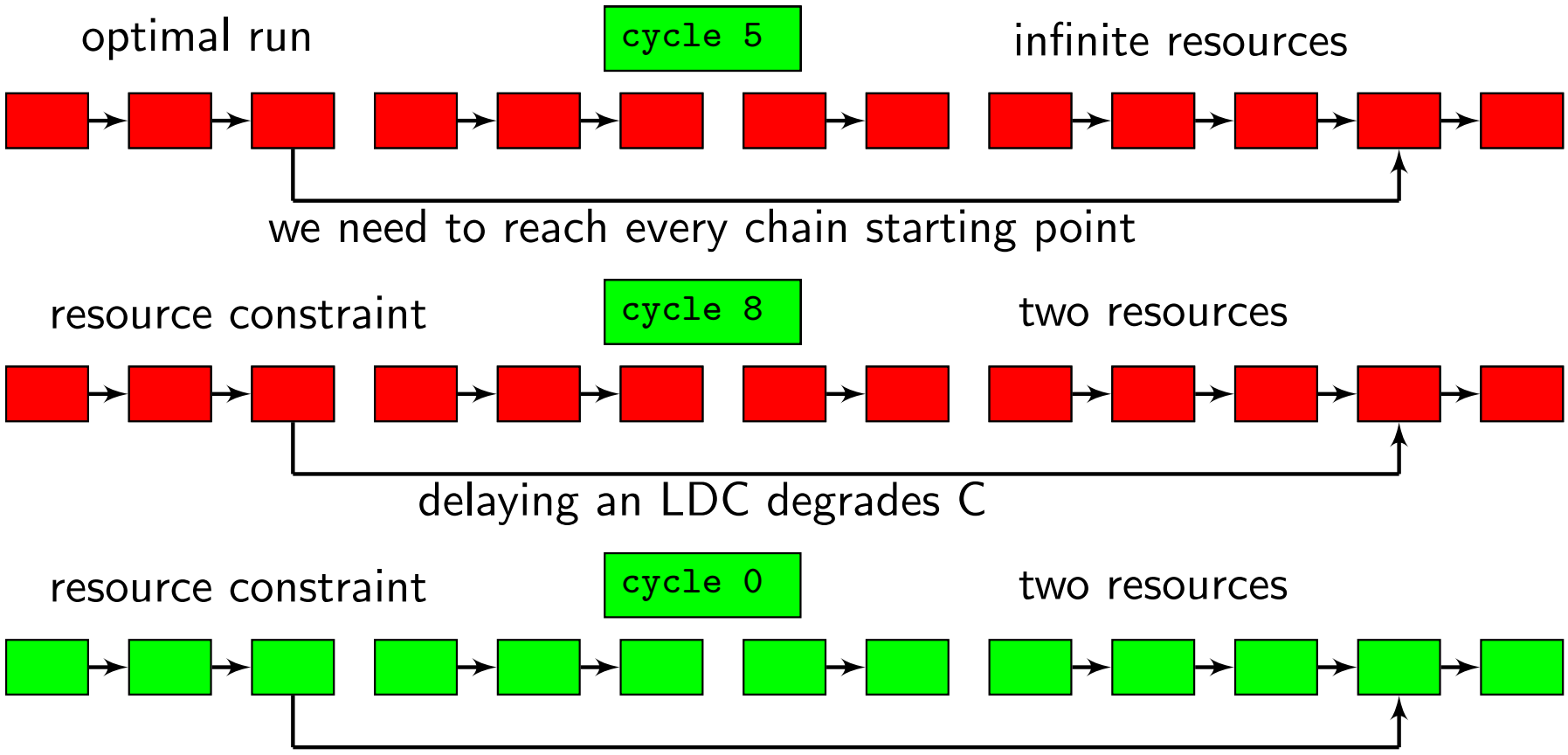

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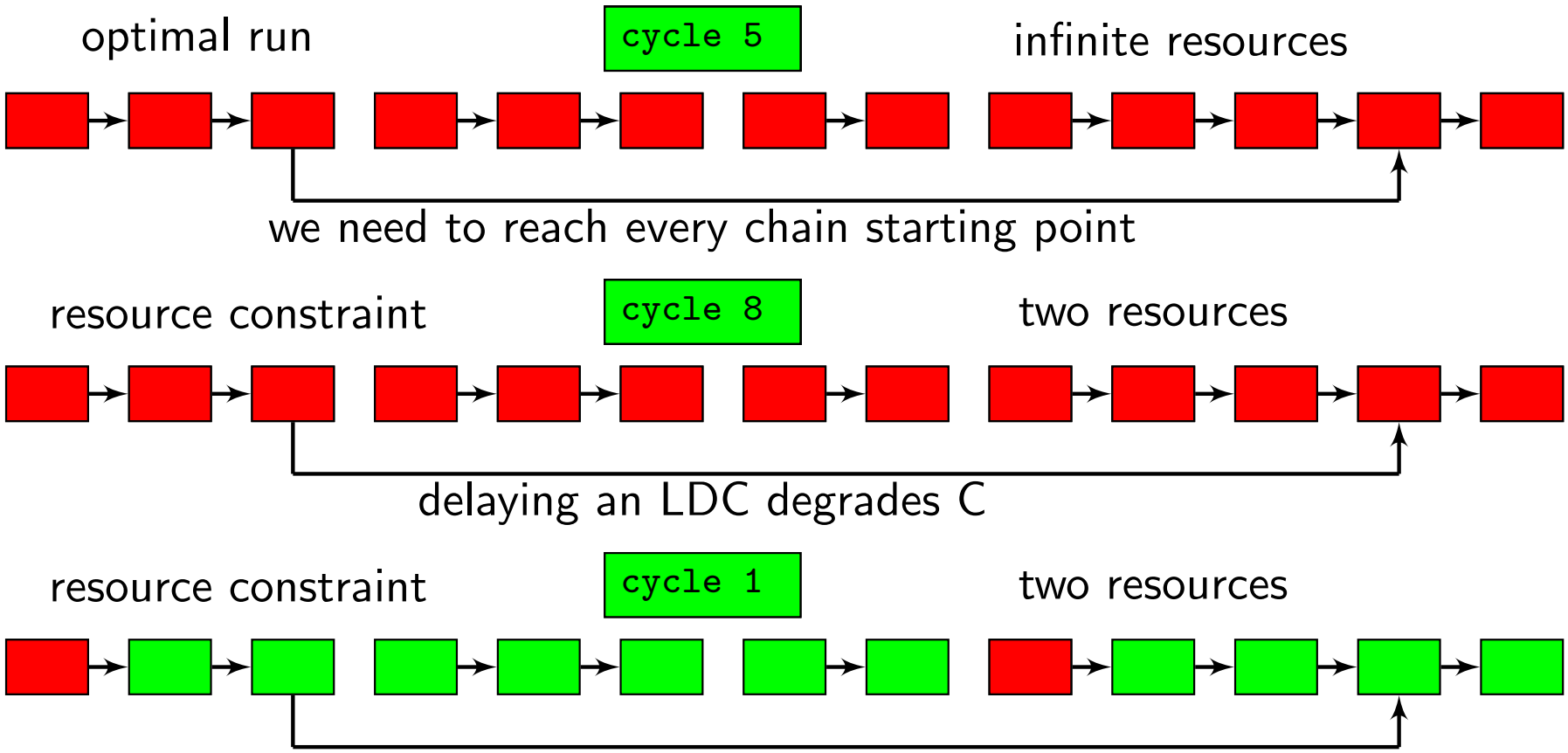

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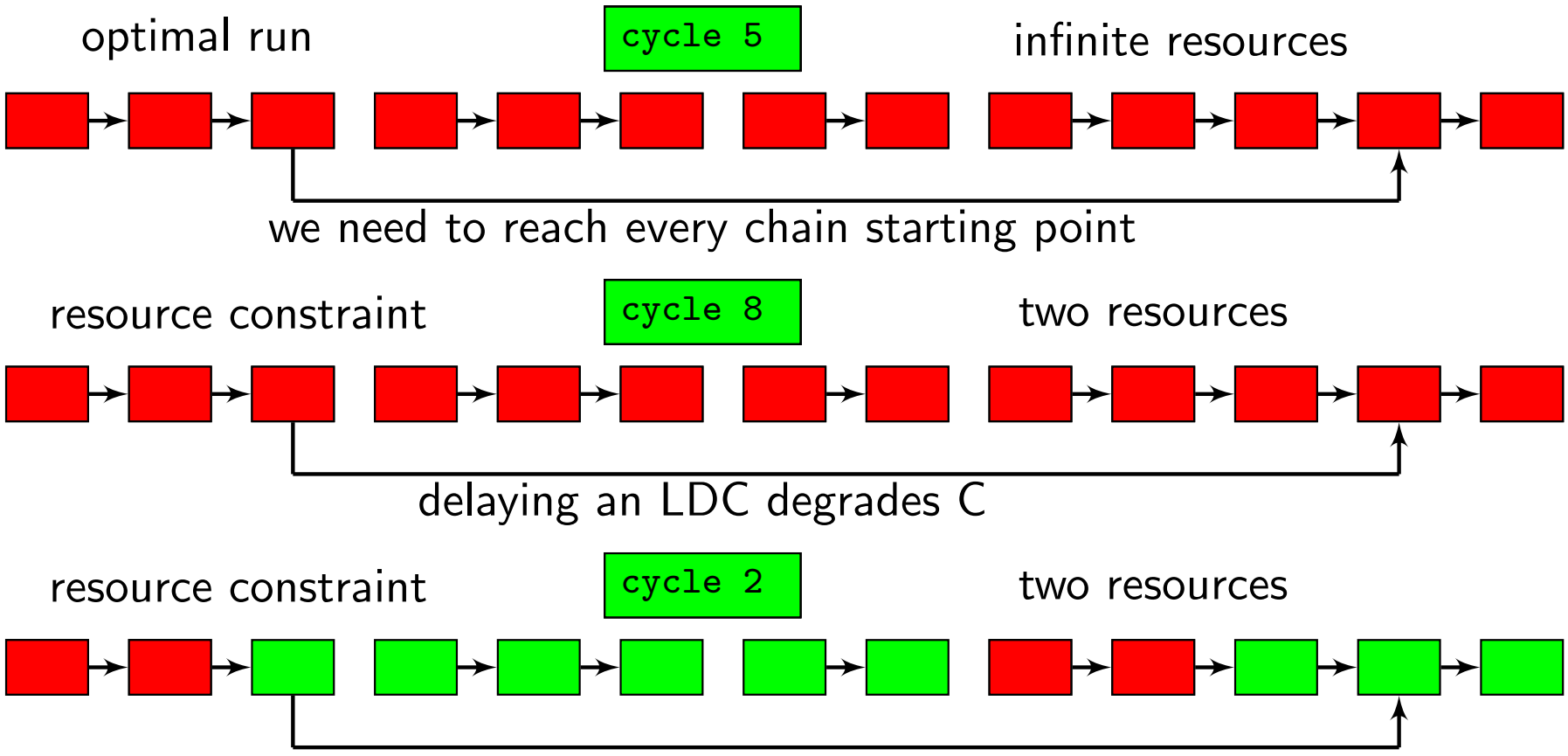

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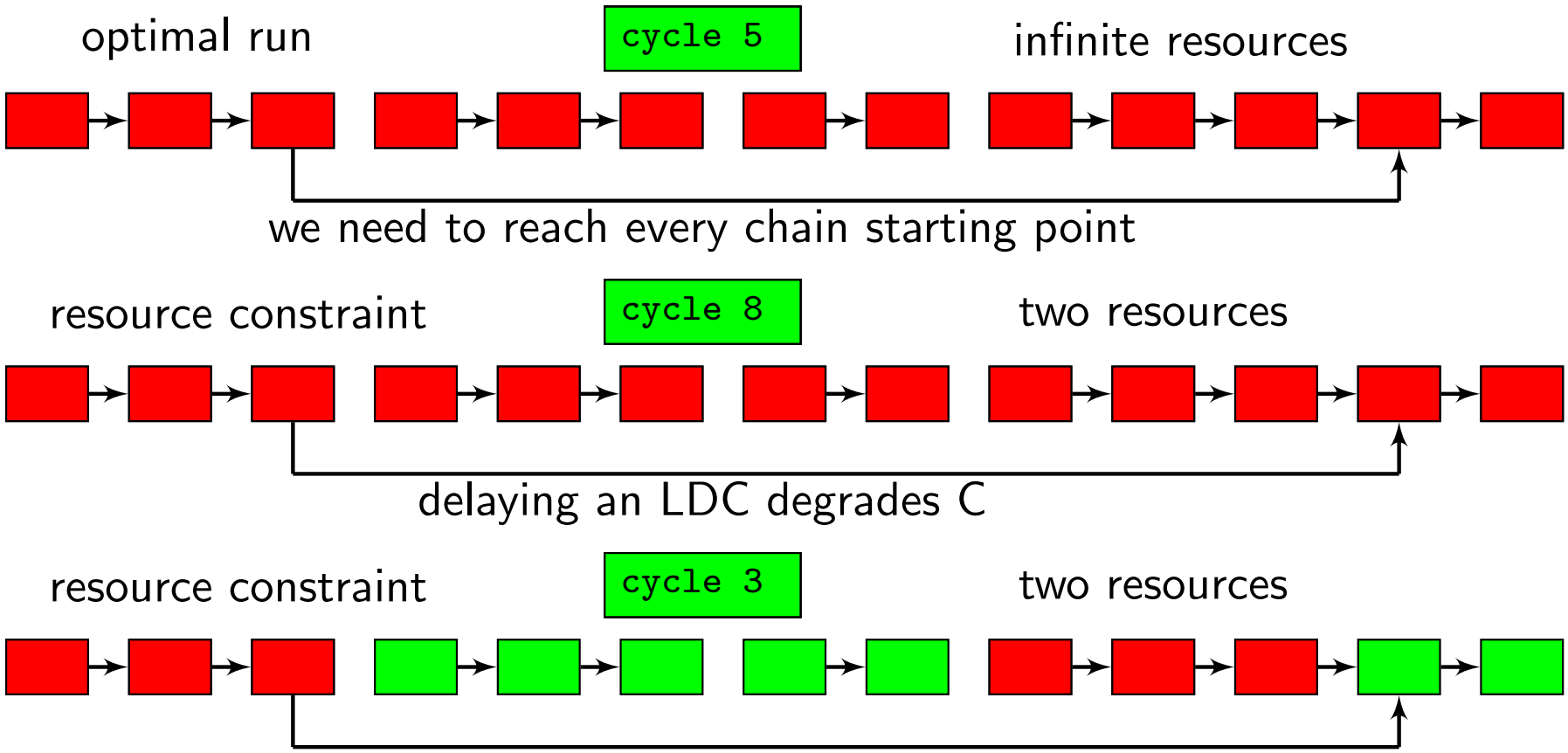

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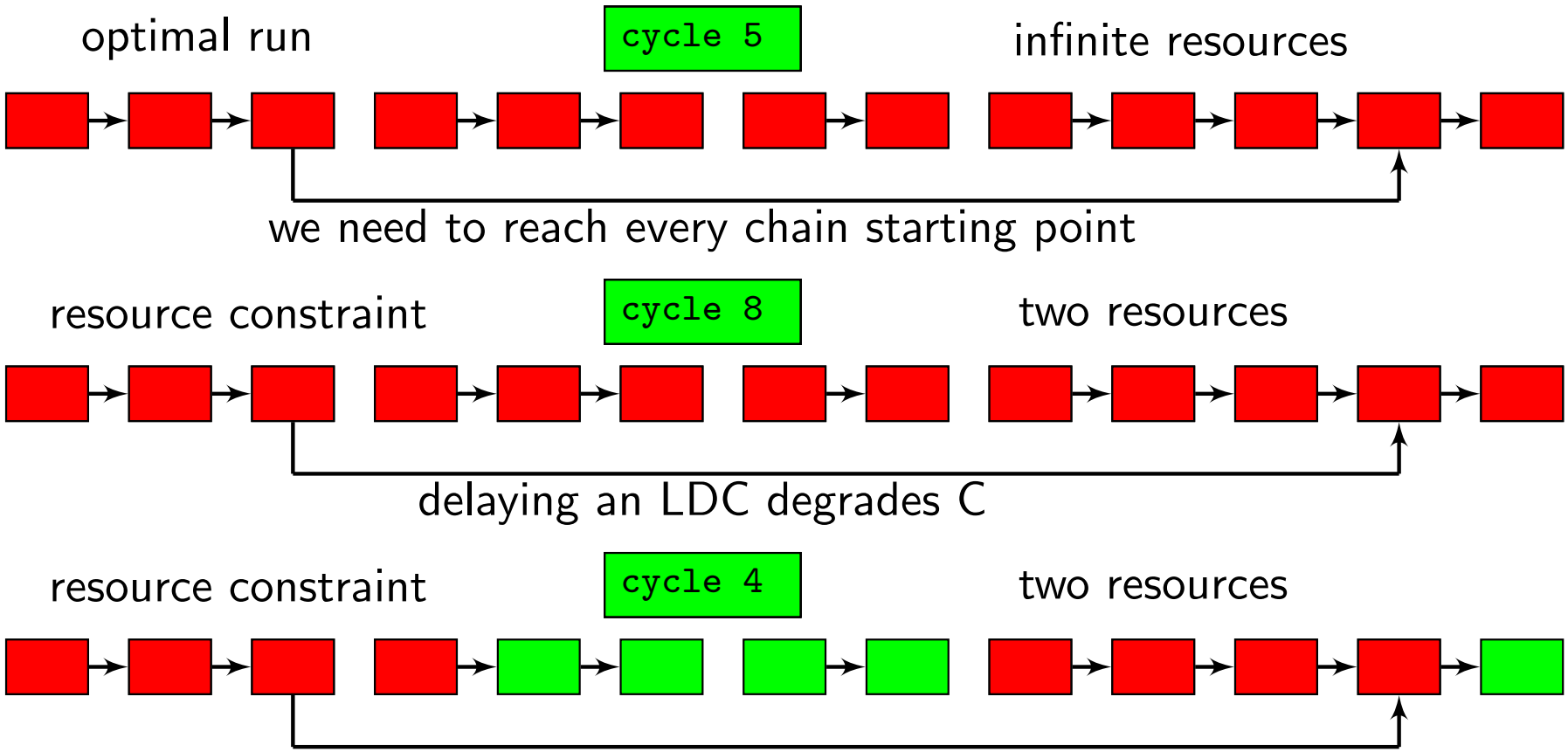

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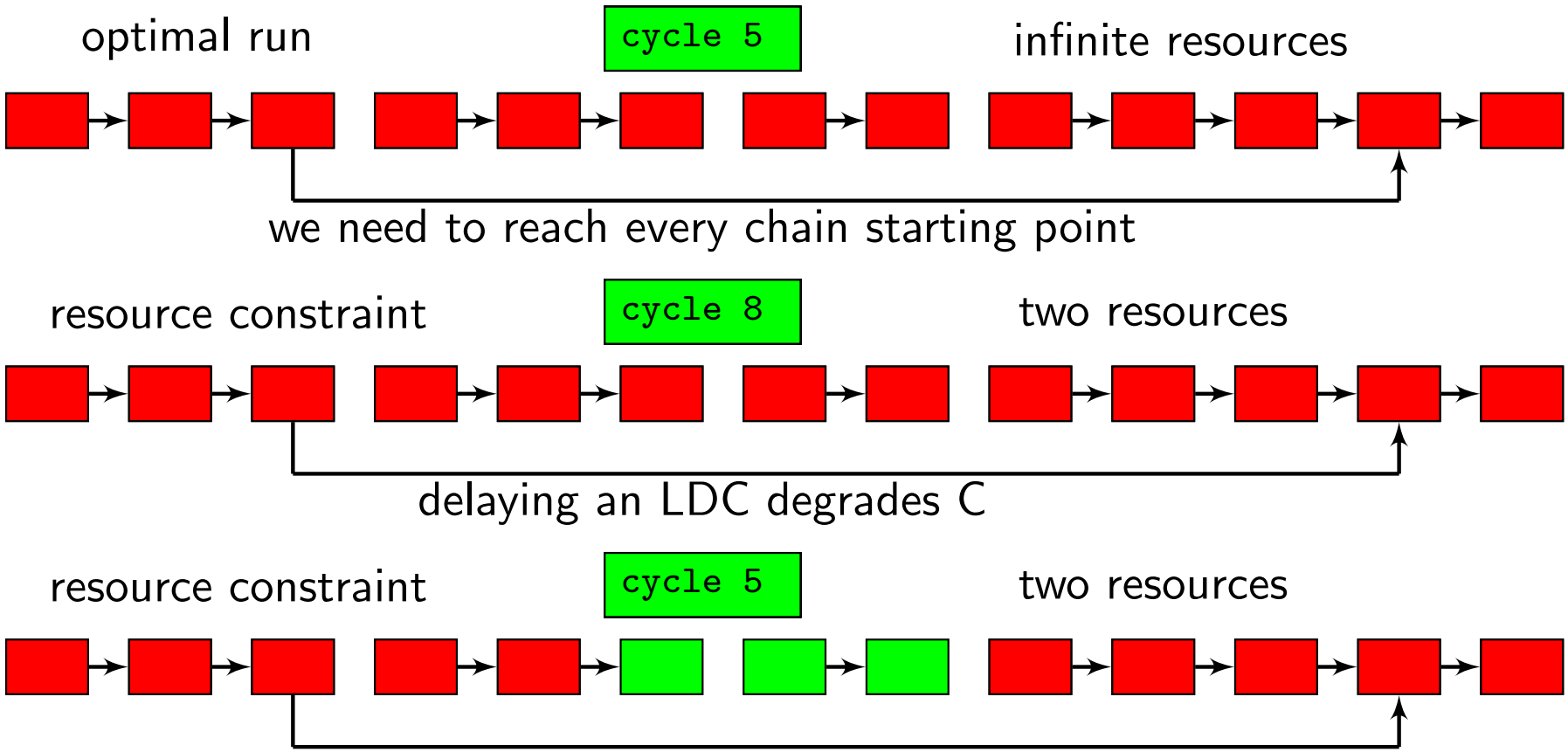

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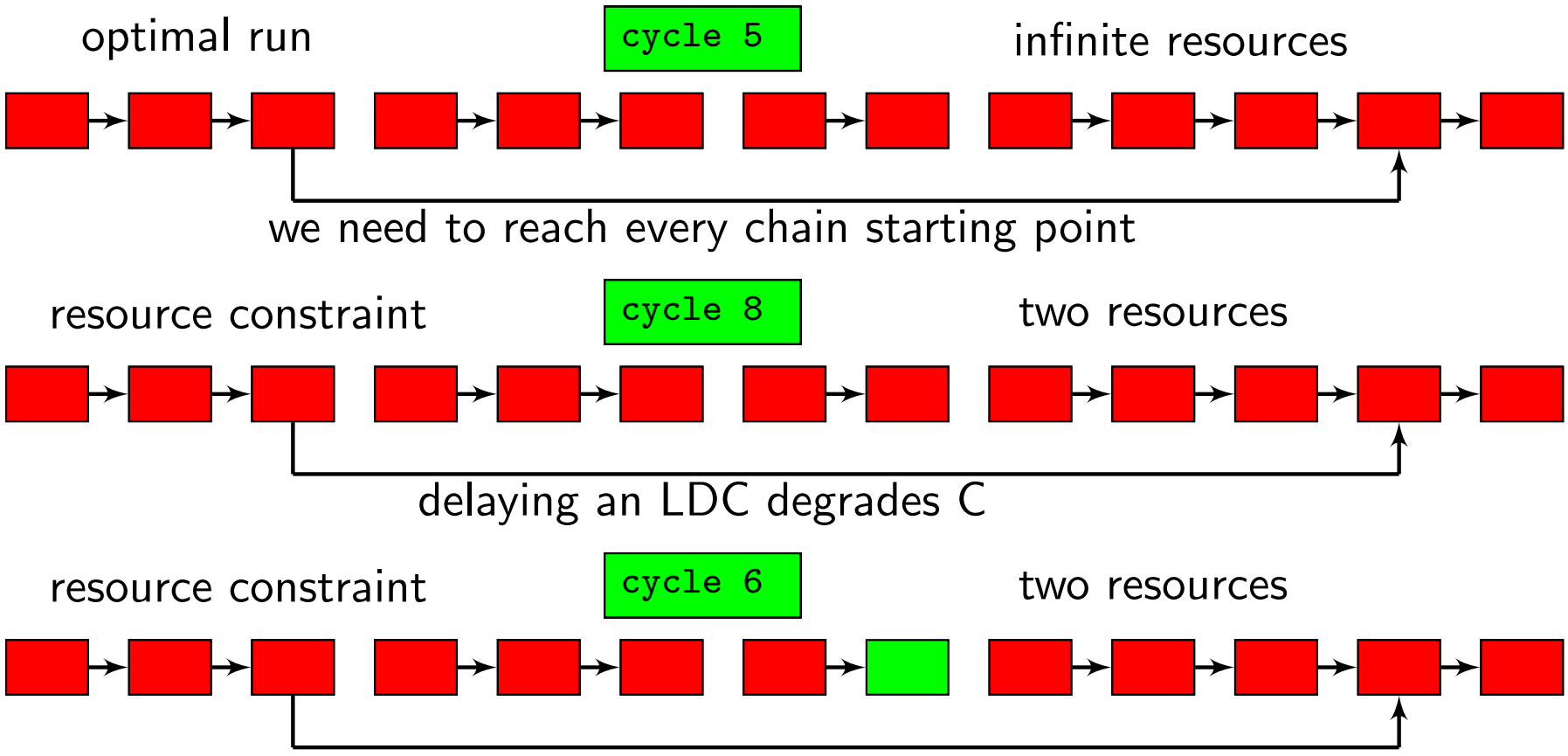

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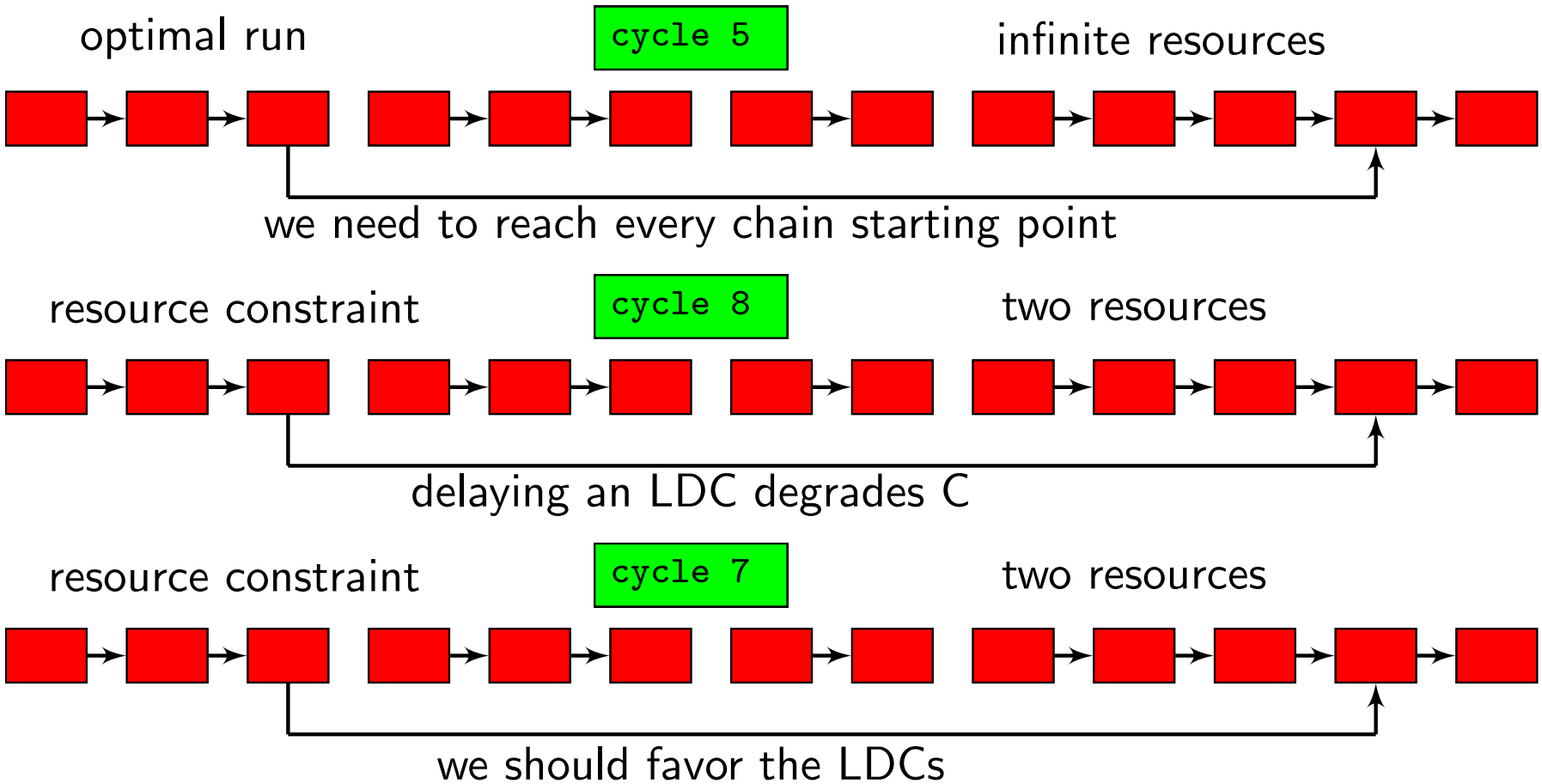

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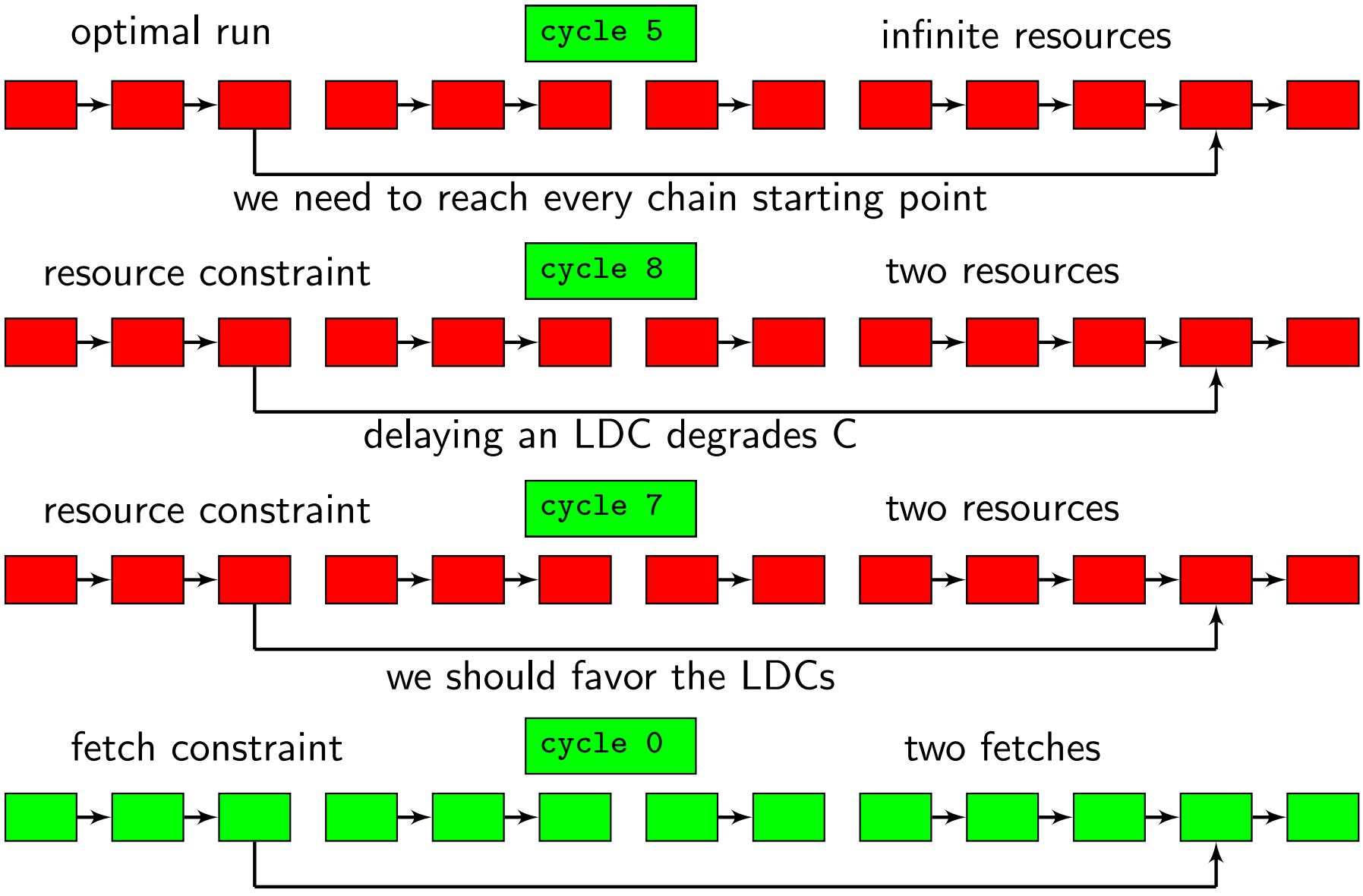

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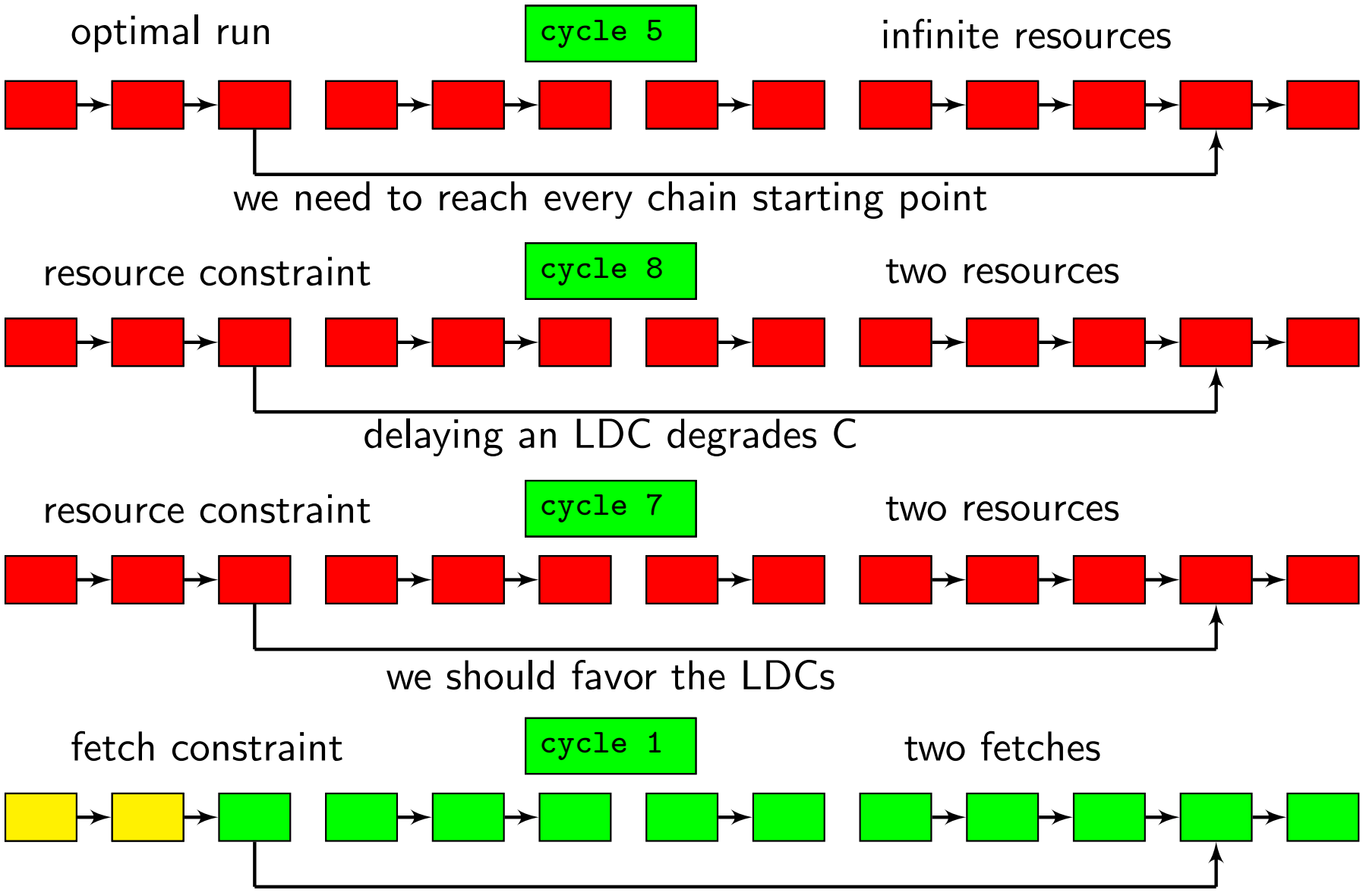

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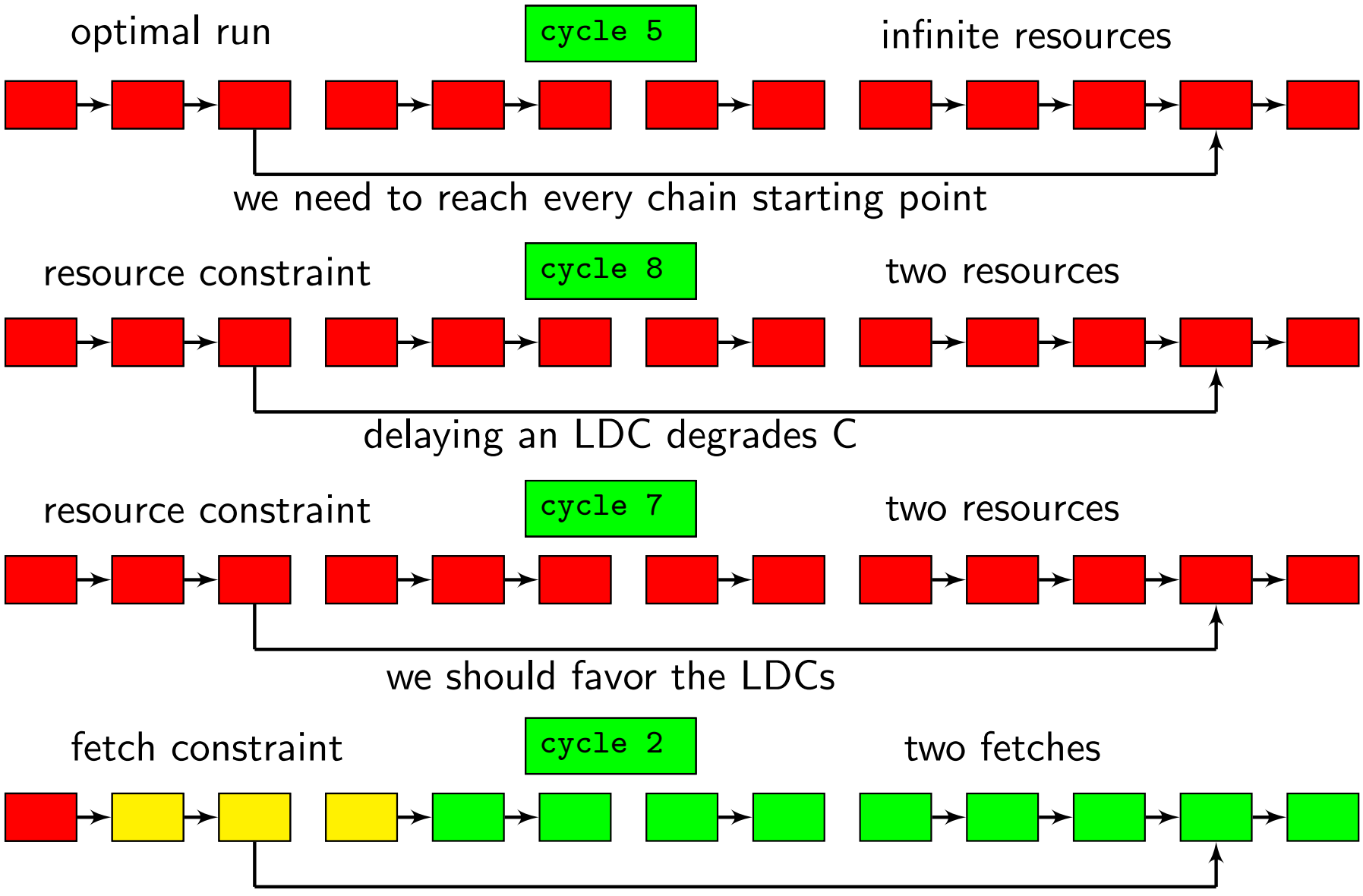

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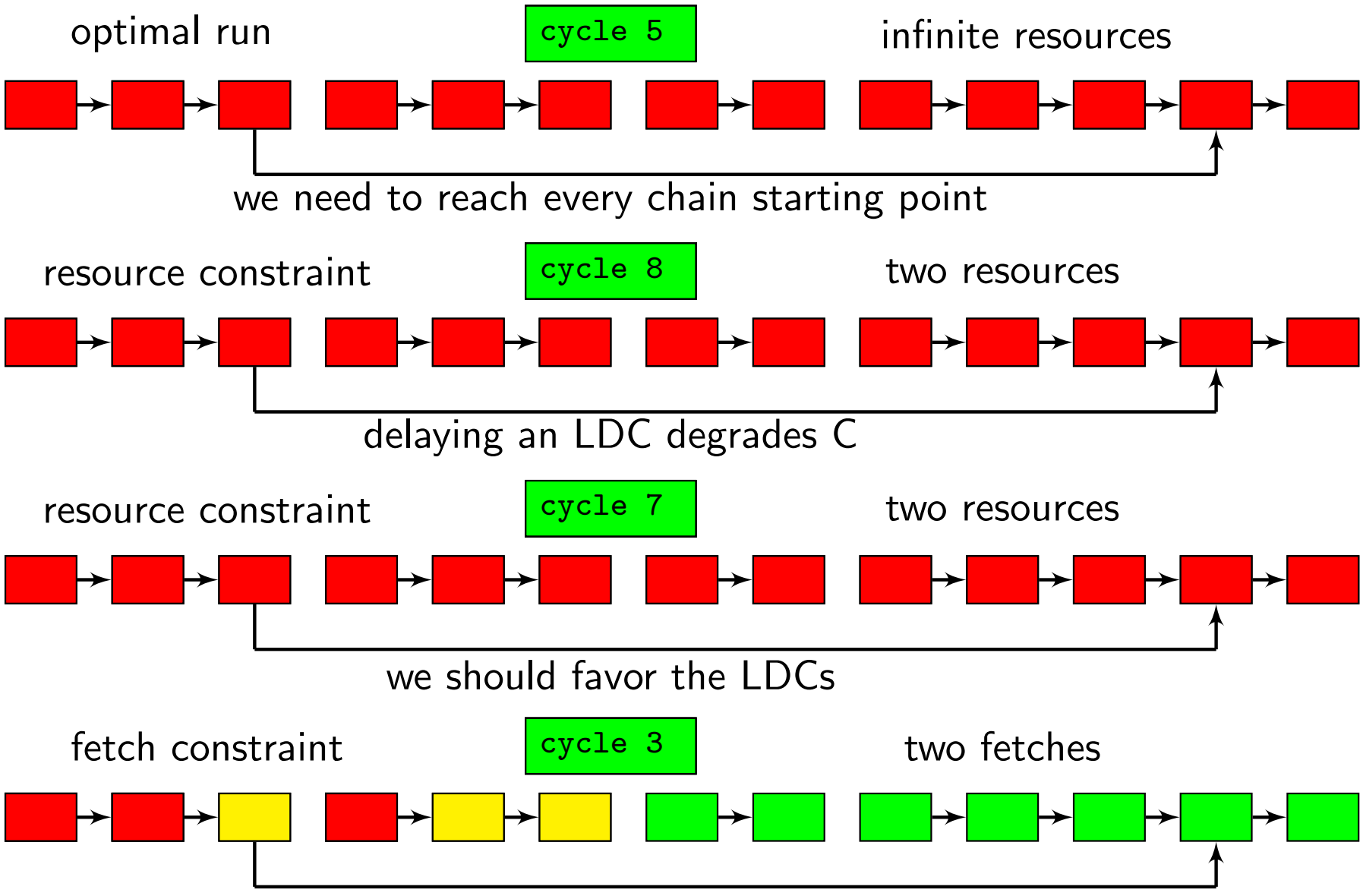

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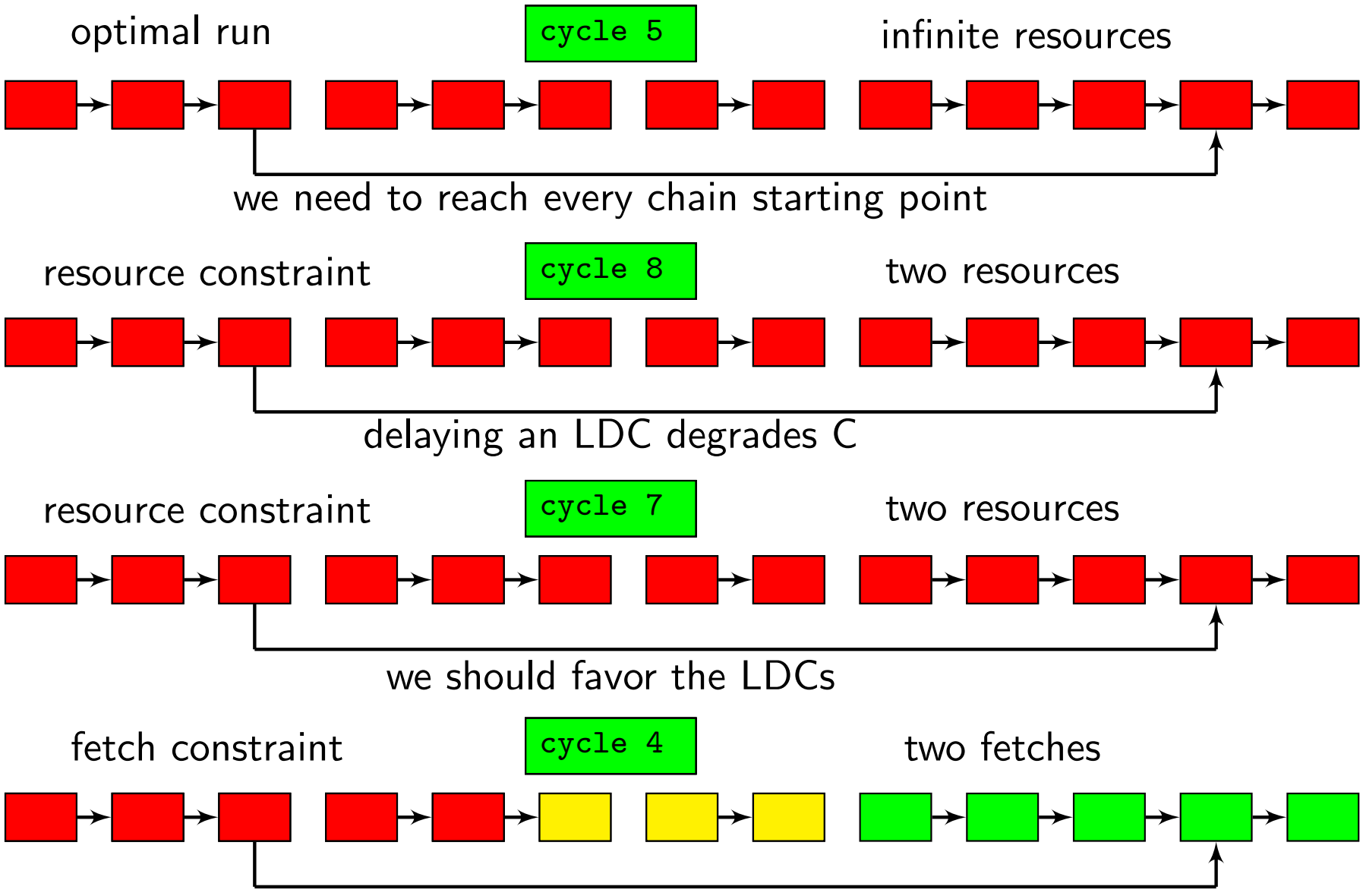

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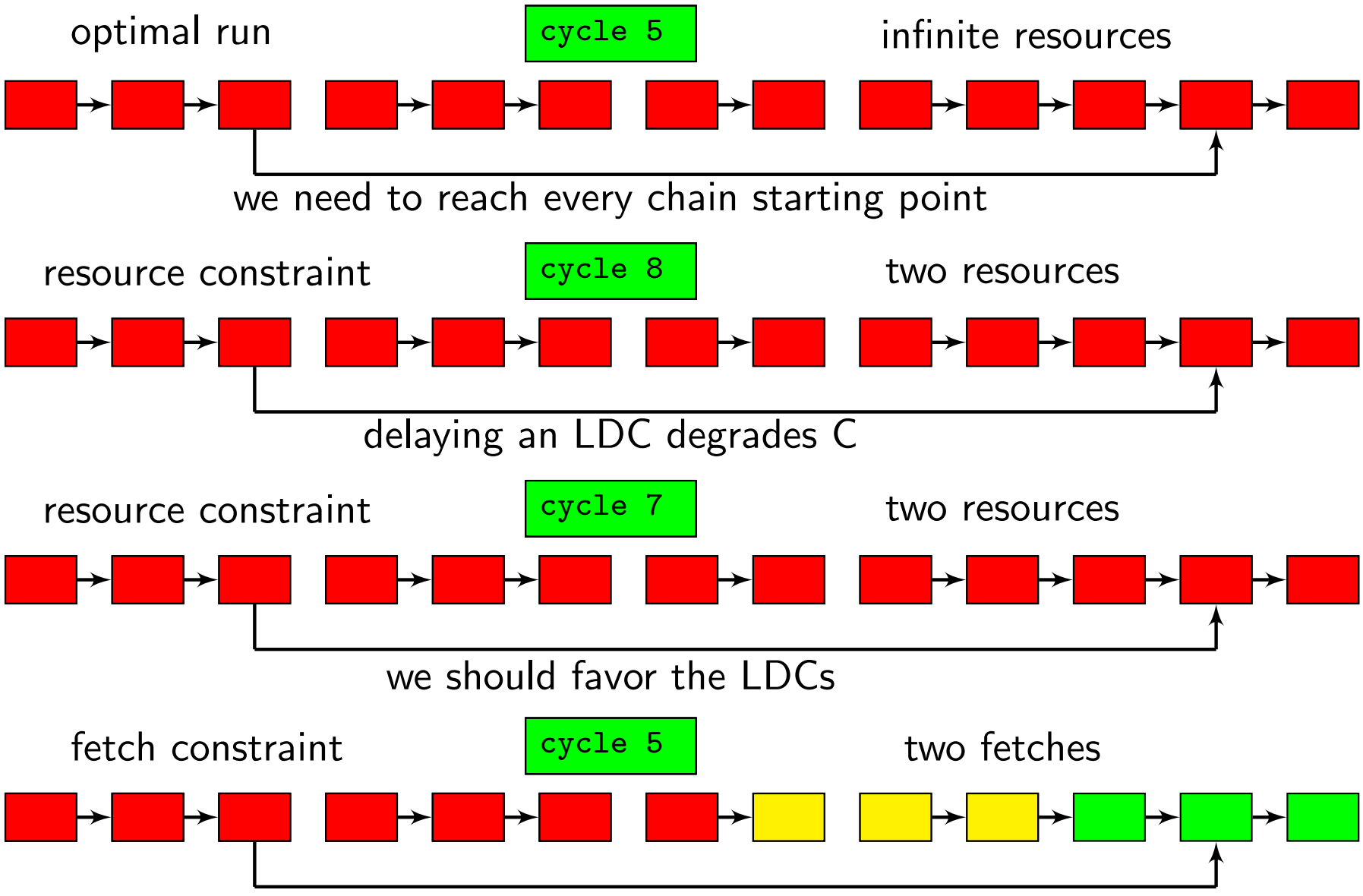

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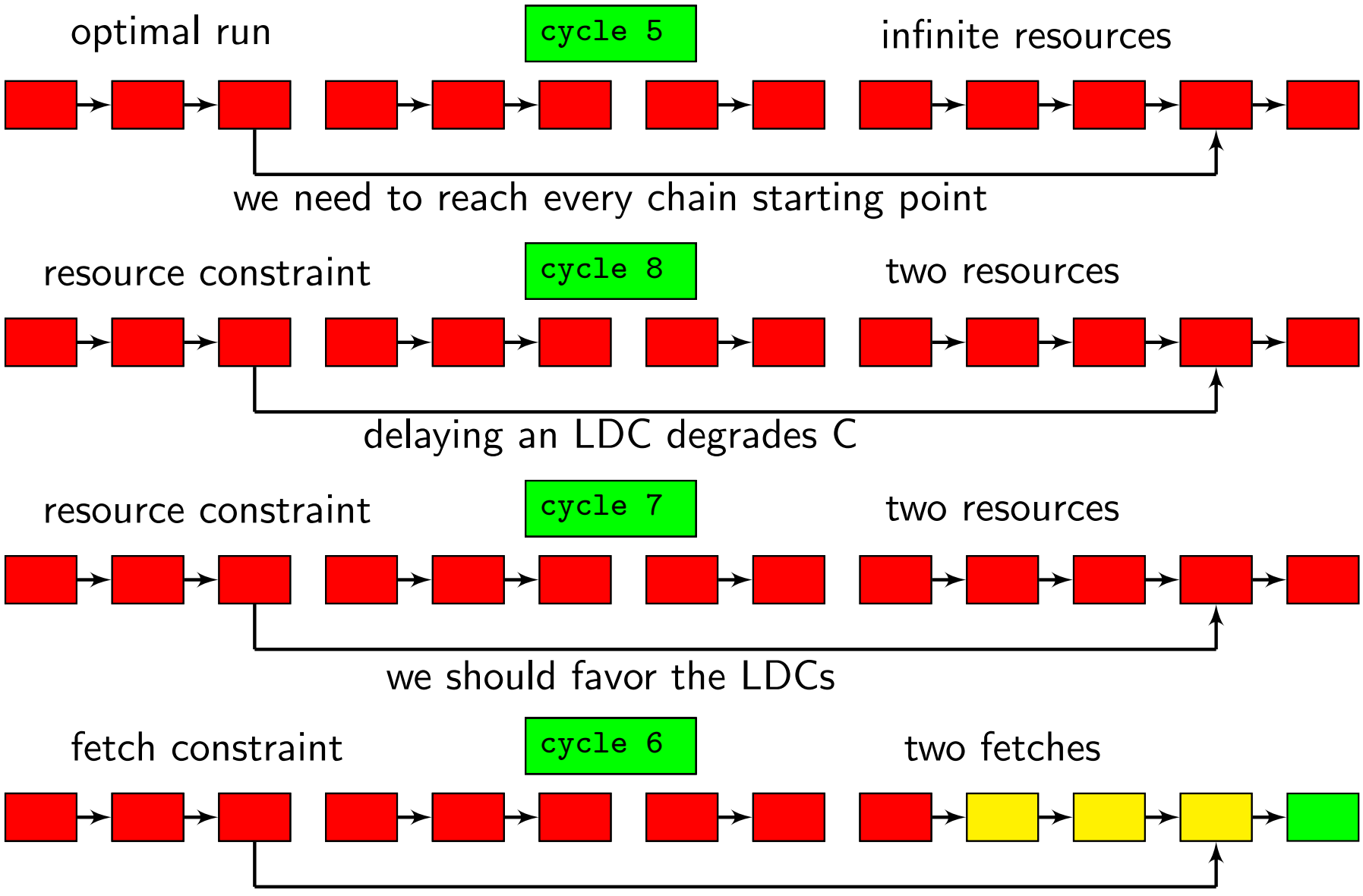

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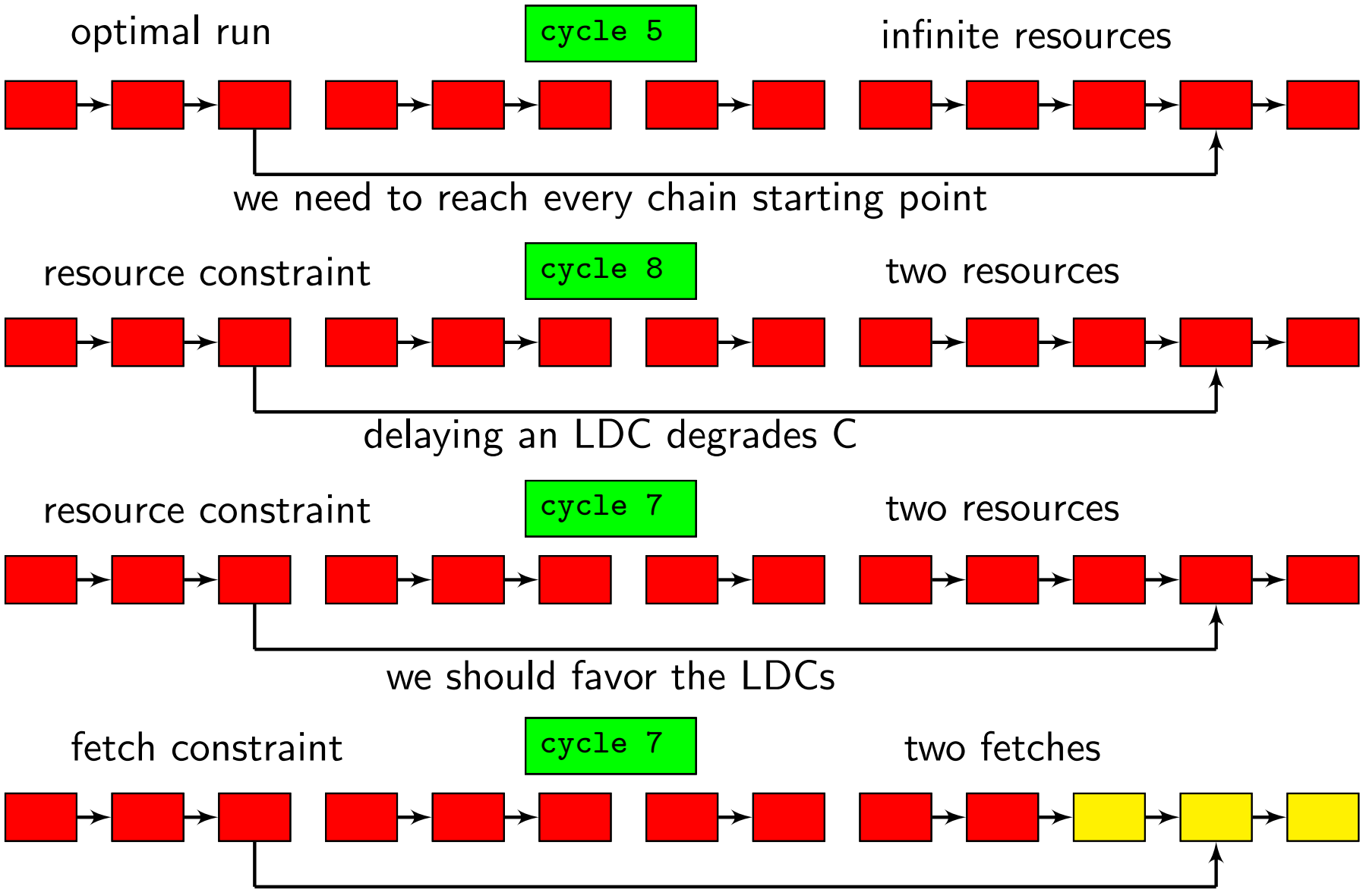

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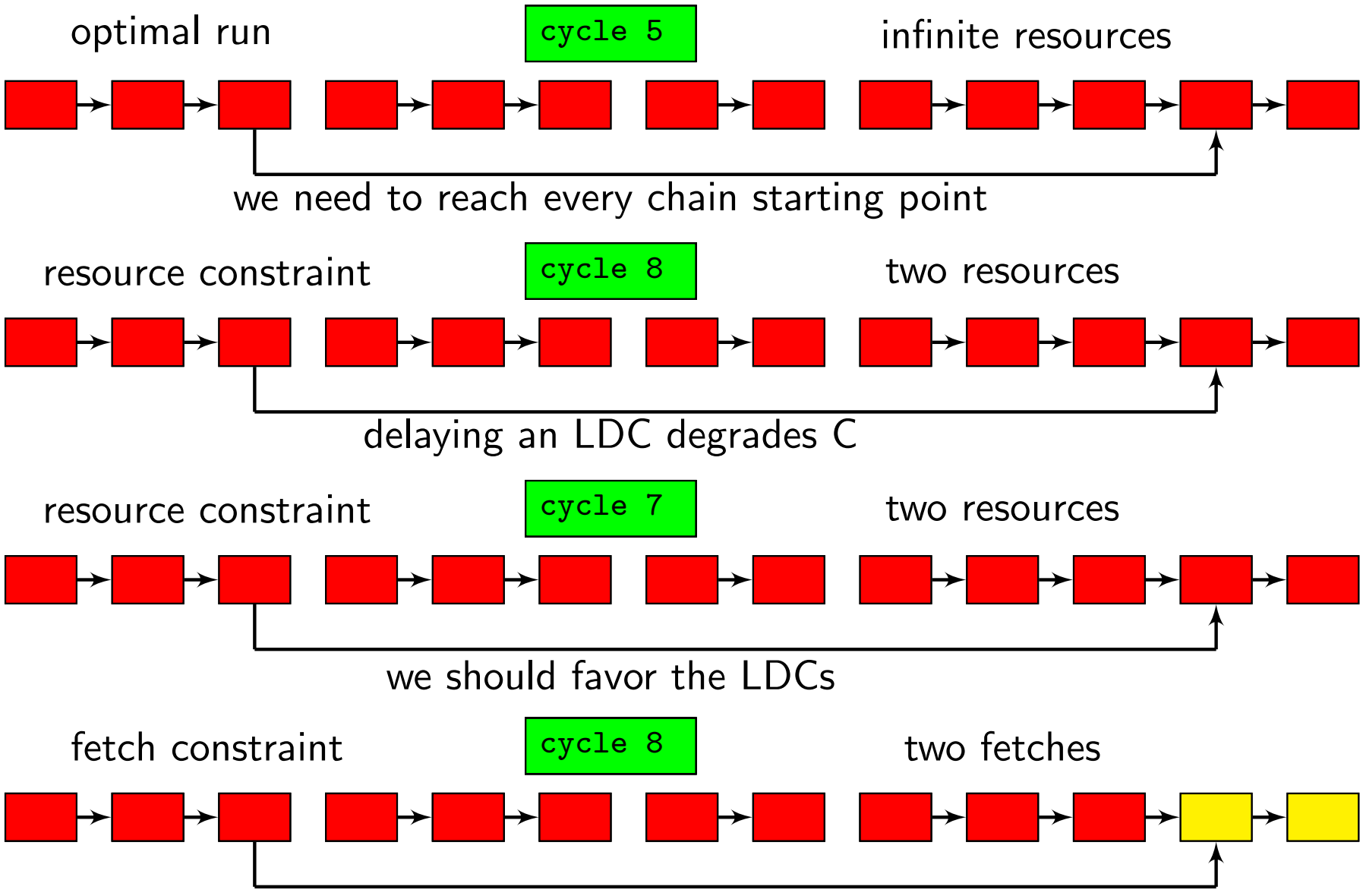

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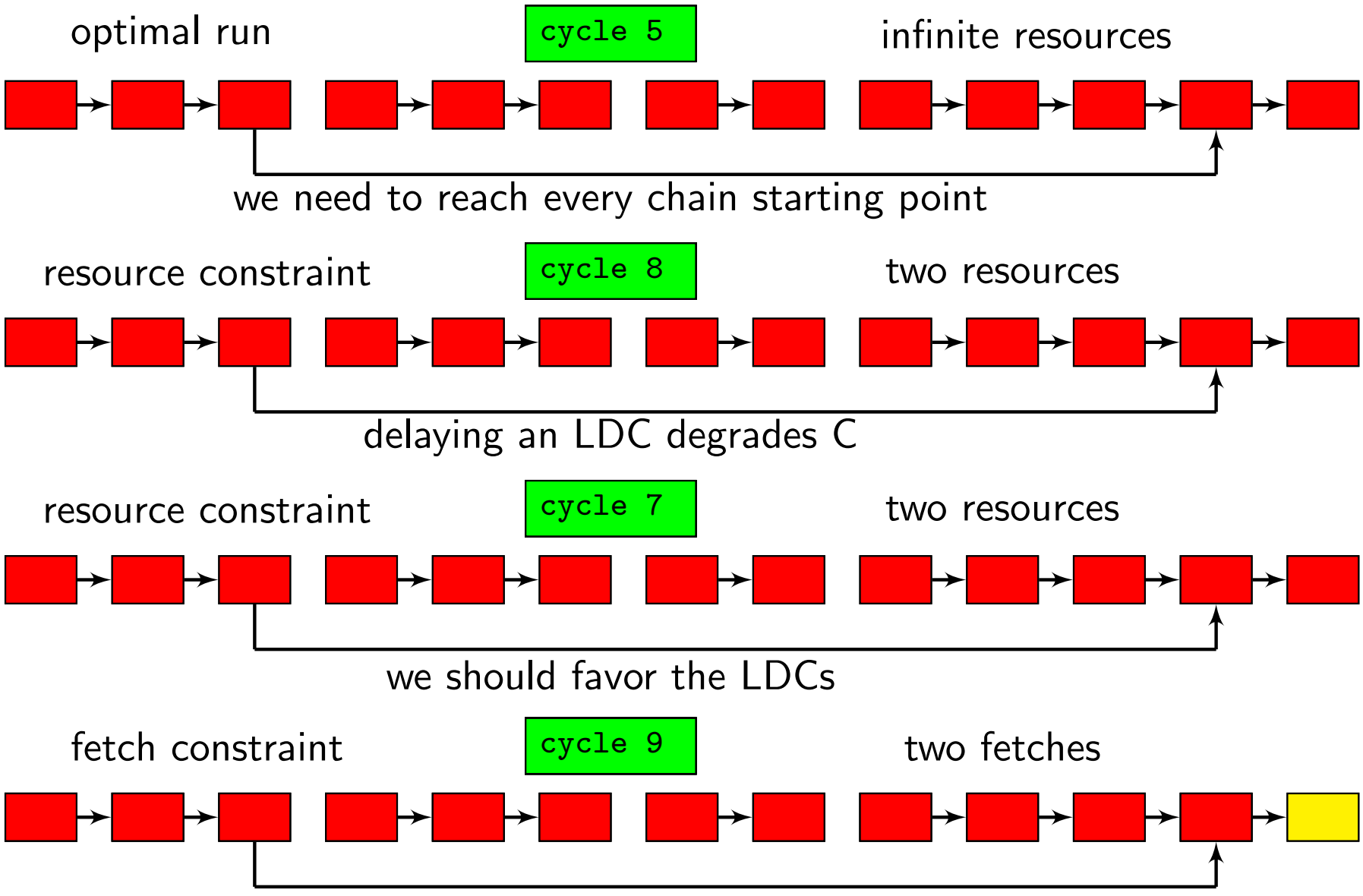

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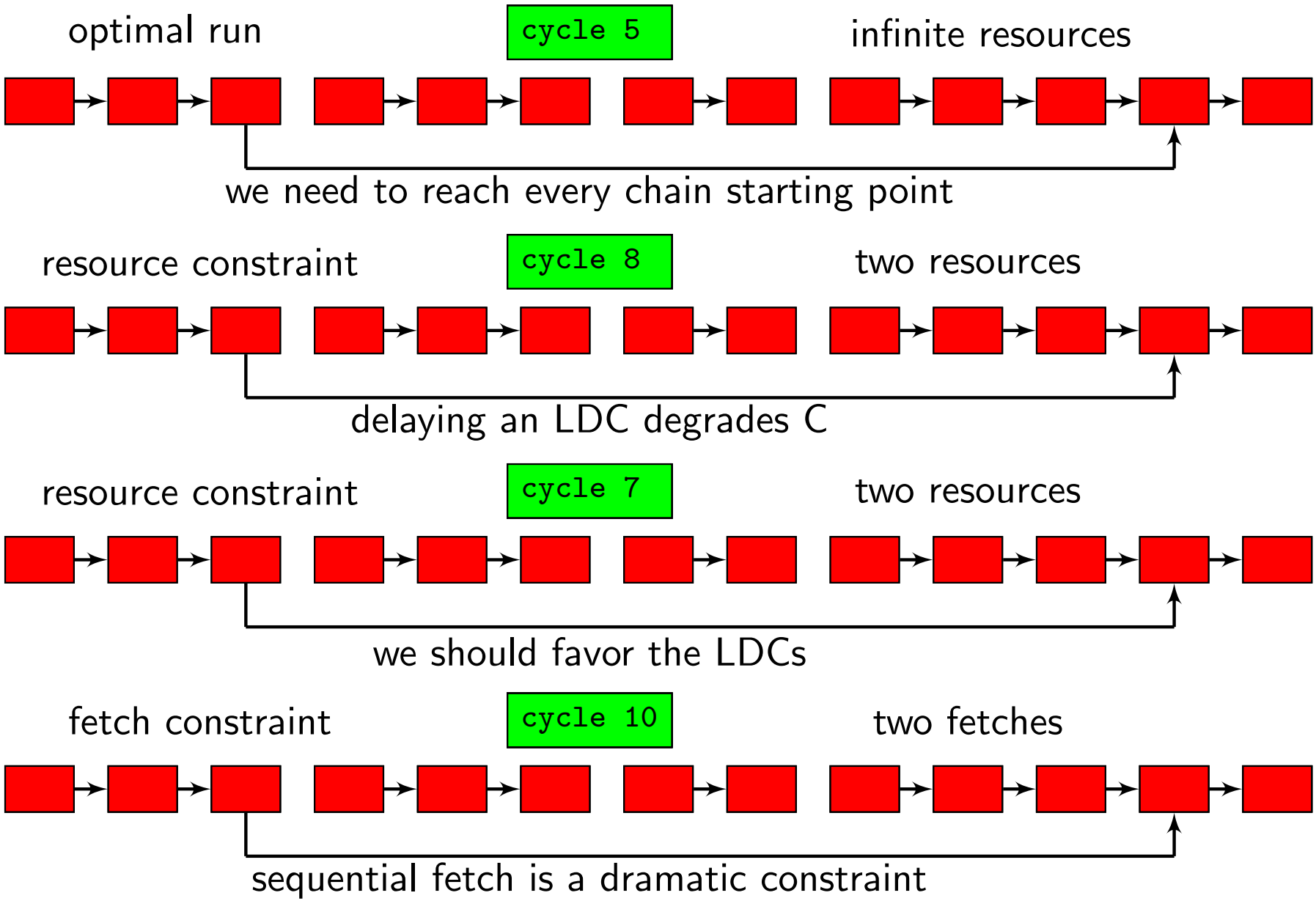

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- Use the return address to fork fetch at every call instruction.
- We must rename dynamic memory places.
- Memory renaming is ideal to match producer/consumer dependent store/load pairs and to parallelize independent accesses.

ILP in for loops : control dependency chain.

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- The control chain starts its run when :
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  - Fetch point has reached the loop (fast forward fetch for late loops).
- The test and conditional branch in the control are delayed if the LIMIT is not a constant.

ILP in for loops.

```
//ILP = 3
for (i=0; i<1024; i++){     //from cycle 1 to 1024, produce i
   ...                      //from cycle 2 to 1025, test i
}                           //from cycle 3 to 1026, cond branch
```

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//ILP = 3
for (i=0; i<1024; i++){      //from cycle 1 to 1024, produce i
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}                            //from cycle 3 to 1026, cond branch

//ILP = 3n/(p+1) <3
//produce n at cycle p-1>n
for (i=0; i<n; i++){         //from cycle 1 to n, produce i
   ...                       //at cycle p, 1024 tests of i
}                            //at cycle p+1, 1024 cond branch
```

ILP in for loops.

```
//ILP = 3
for (i=0; i<1024; i++){     //from cycle 1 to 1024, produce i
   ...                      //from cycle 2 to 1025, test i
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//ILP = 3n/(p+1) <3
//produce n at cycle p-1>n
for (i=0; i<n; i++){        //from cycle 1 to n, produce i
   ...                      //at cycle p, 1024 tests of i
}                           //at cycle p+1, 1024 cond branch

//ILP = 3n/(p+1) <3
//produce j at cycle q-1>n
//produce n at cycle p-1>q+1024
for (i=j; i<n; i++){        //from cycle q to q+1024, produce i
   ...                      //at cycle p, 1024 tests of i
}                           //at cycle p+1, 1024 cond branch
```

ILP in for loops.

```
//ILP = 3
for (i=0; i<1024; i++){     //from cycle 1 to 1024, produce i
  ...                       //from cycle 2 to 1025, test i
}                           //from cycle 3 to 1026, cond branch

//ILP = 3n/(p+1) <3
//produce n at cycle p-1>n
for (i=0; i<n; i++){        //from cycle 1 to n, produce i
  ...                       //at cycle p, 1024 tests of i
}                           //at cycle p+1, 1024 cond branch

//ILP = 3n/(p+1) <3
//produce j at cycle q-1>n
//produce n at cycle p-1>q+1024
for (i=j; i<n; i++){        //from cycle q to q+1024, produce i
  ...                       //at cycle p, 1024 tests of i
}                           //at cycle p+1, 1024 cond branch

//ILP = 3*1024
//nested loops are vectorized
for (i=0; i<1024; i++){     //from cycle 1 to 1024, produce i
  for (j=0; j<1024; j++){   //from cycle 1 to 1024, produce 1024 j
    ...                     //from cycle 2 to 1024, test 1024 j
  }                         //from cycle 3 to 1026, 1024 cond branch
  ...                       //from cycle 2 to 1024, test i
}                           //from cycle 3 to 1026, cond branch
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- Loops controls are often independent and can be run in parallel.

Nested loops.

```
        ...                 ; x computed in al      x=f(...);
        movl $0, %esi       ; i=0                   for (i=0;i<1024;i++)
.L5:    ; external loop start                         for (j=0;j<1024;j++)
        movl $0, %edi       ; j=0                       t[i][j]=x;
.L4:    ; internal loop start
        movl %esi, %ecx     ; ecx=i
        sall $10, %ecx      ; ecx=ecx*1024
        addl %edi, %ecx     ; ecx=ecx+j
        movb %al, t(%ecx)   ; t[i][j]=x
        addl $1, %edi       ; j++
        cmpl $1024, %edi    ; (j == 1024)
        jne  .L4            ; if (j!=1024) goto .L4
        ; internal loop end
        addl $1, %esi       ; i++
        cmpl $1024, %esi    ; (i == 1024)
        jne  .L5            ; if (i!=1024) goto .L5
        ; external loop end
```

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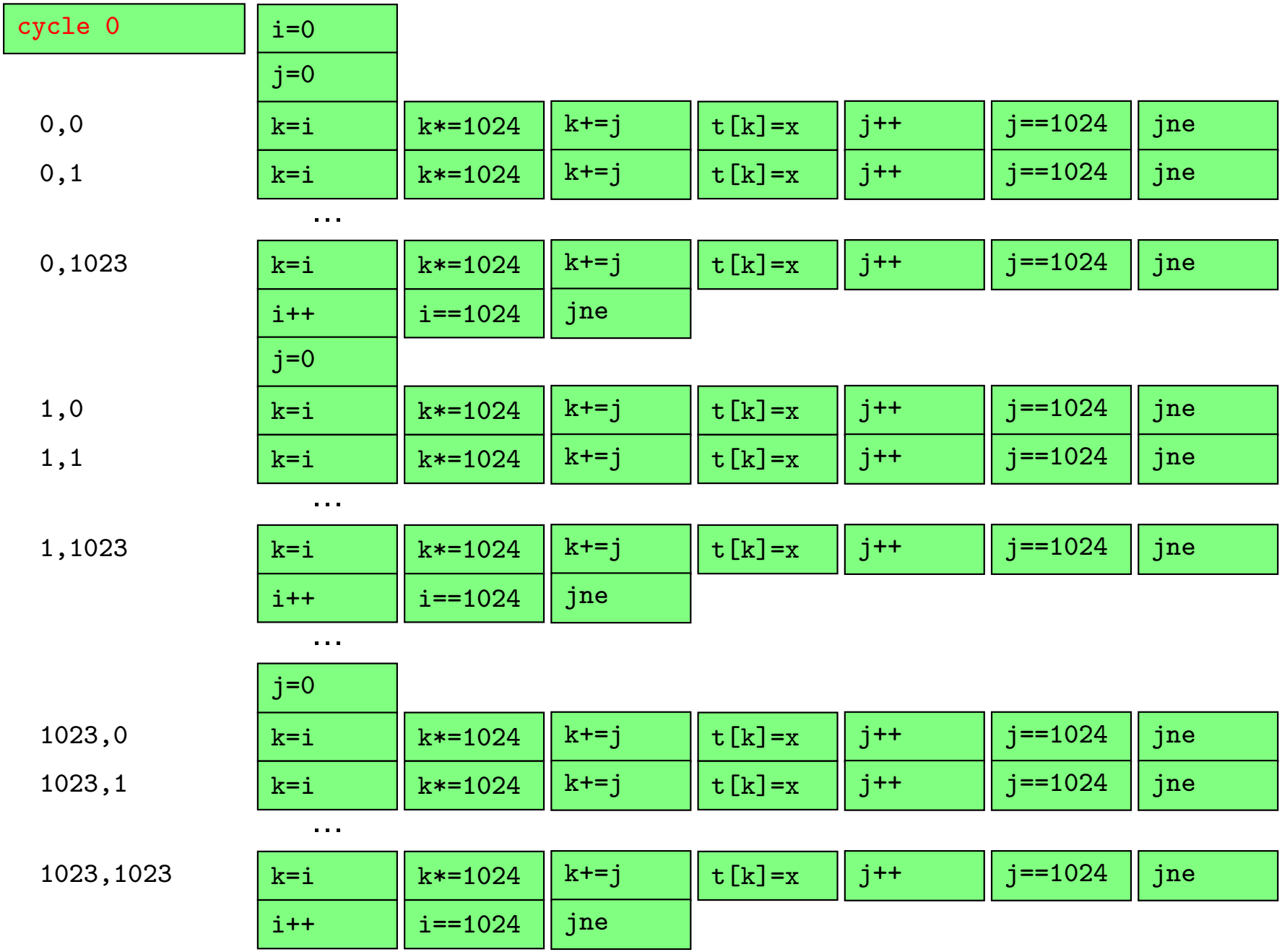

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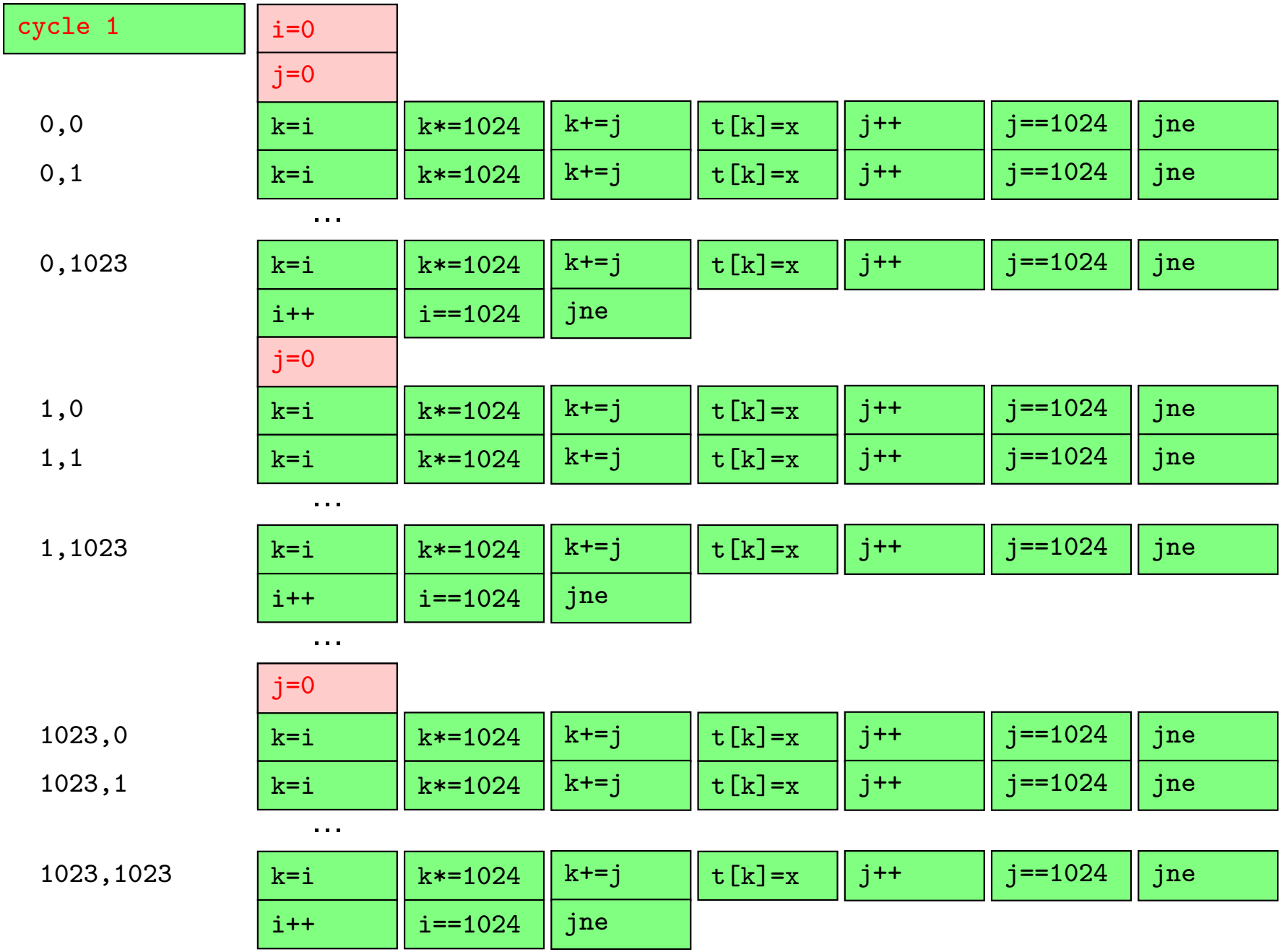

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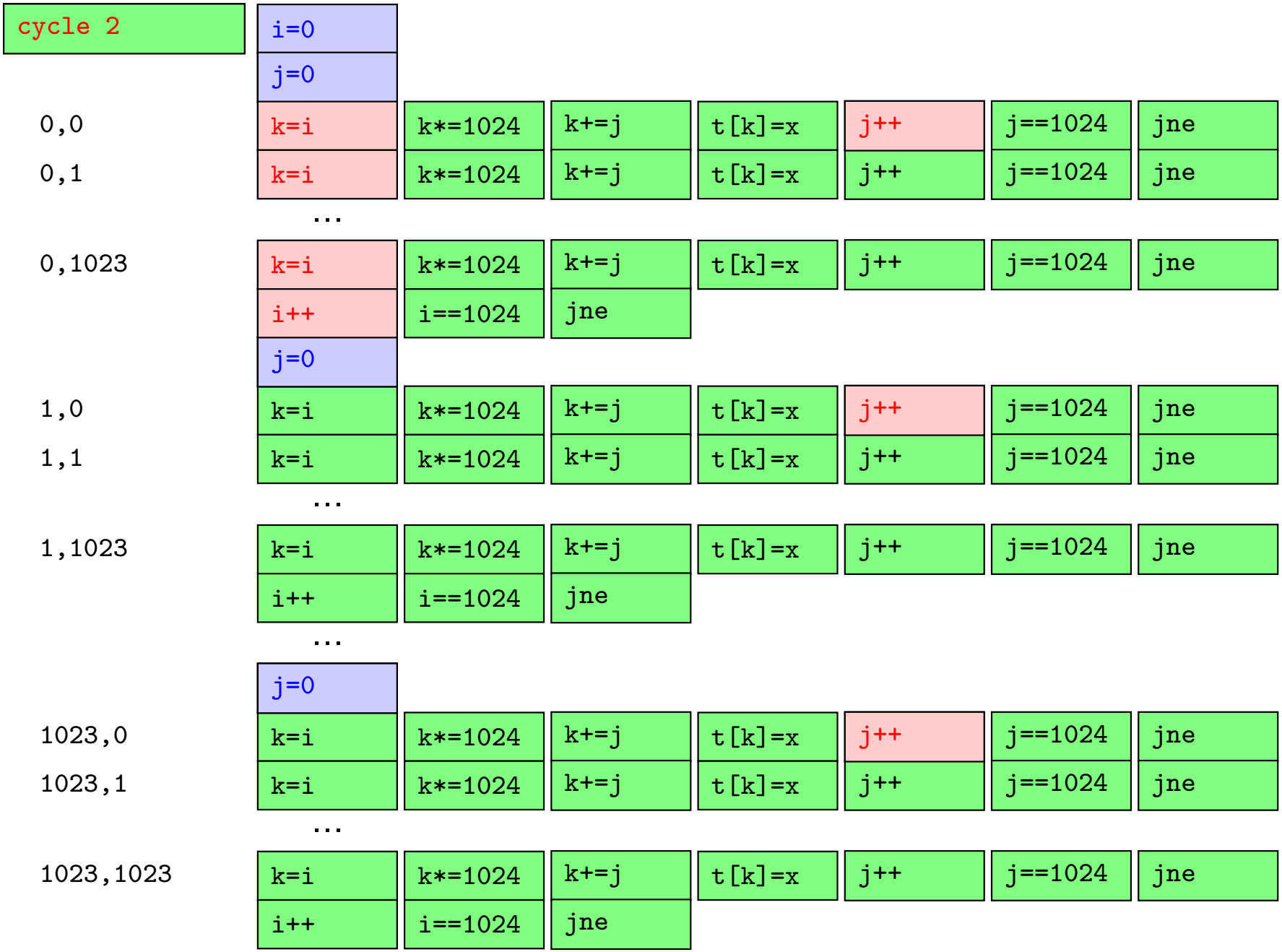

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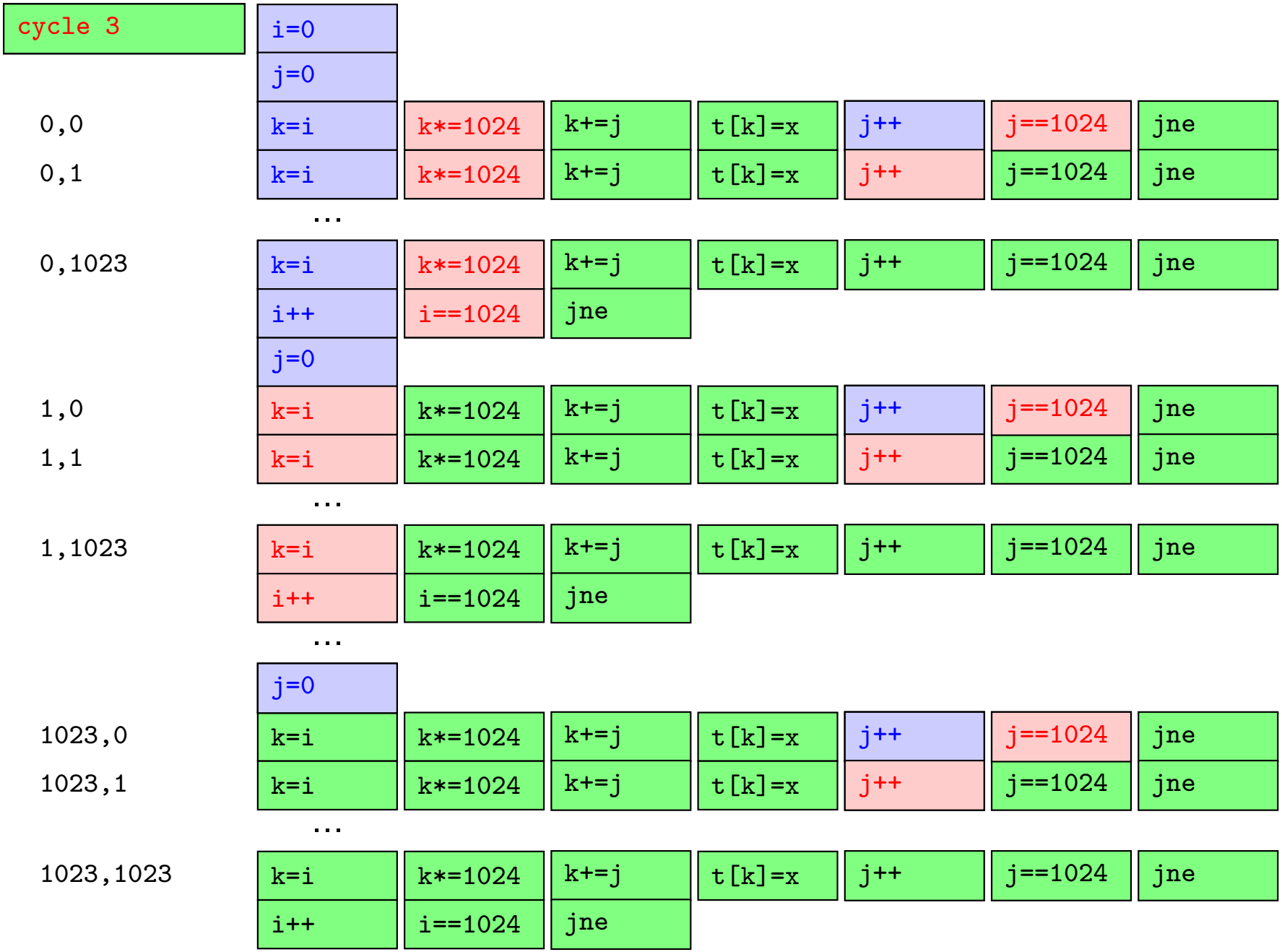

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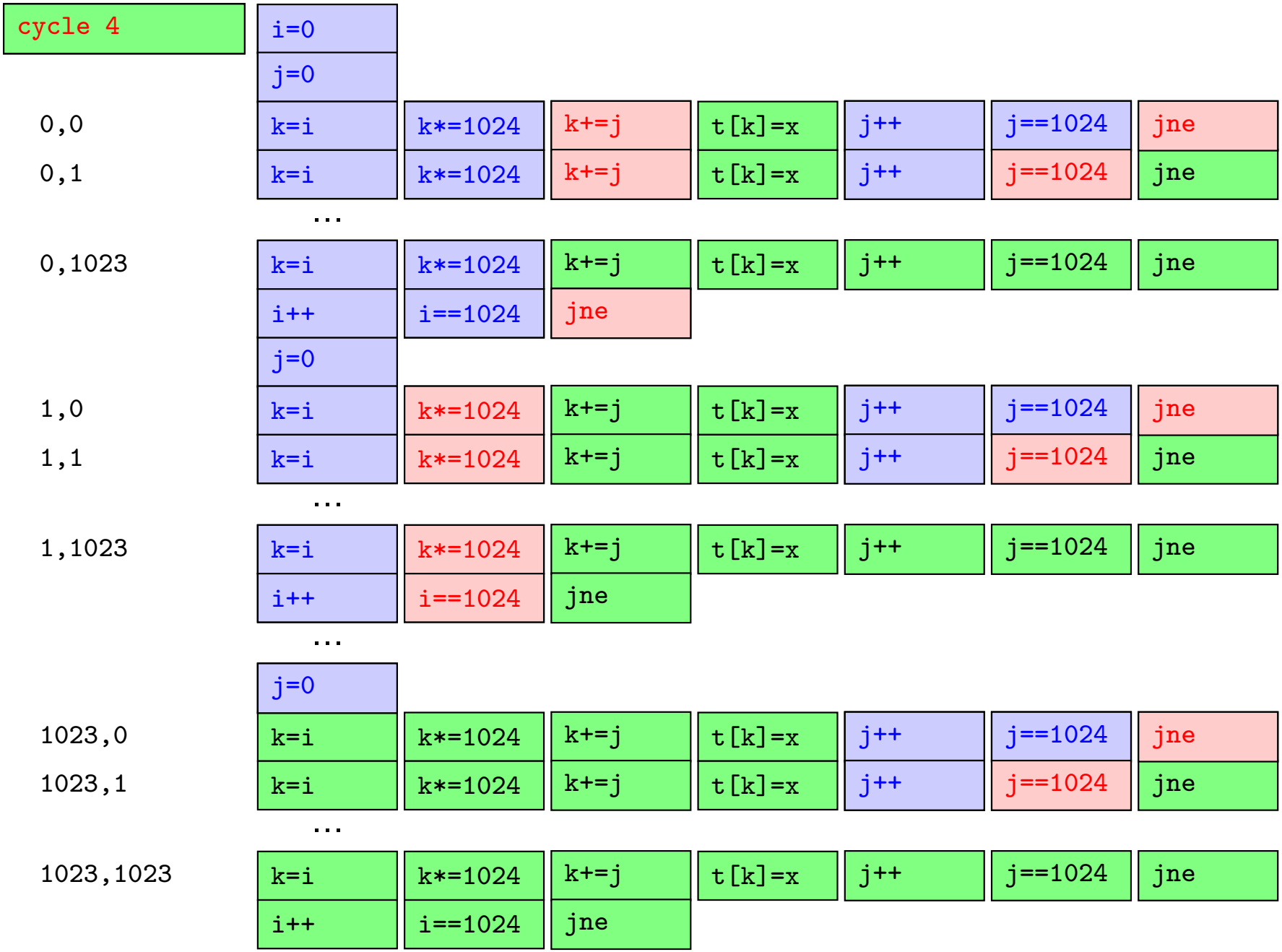

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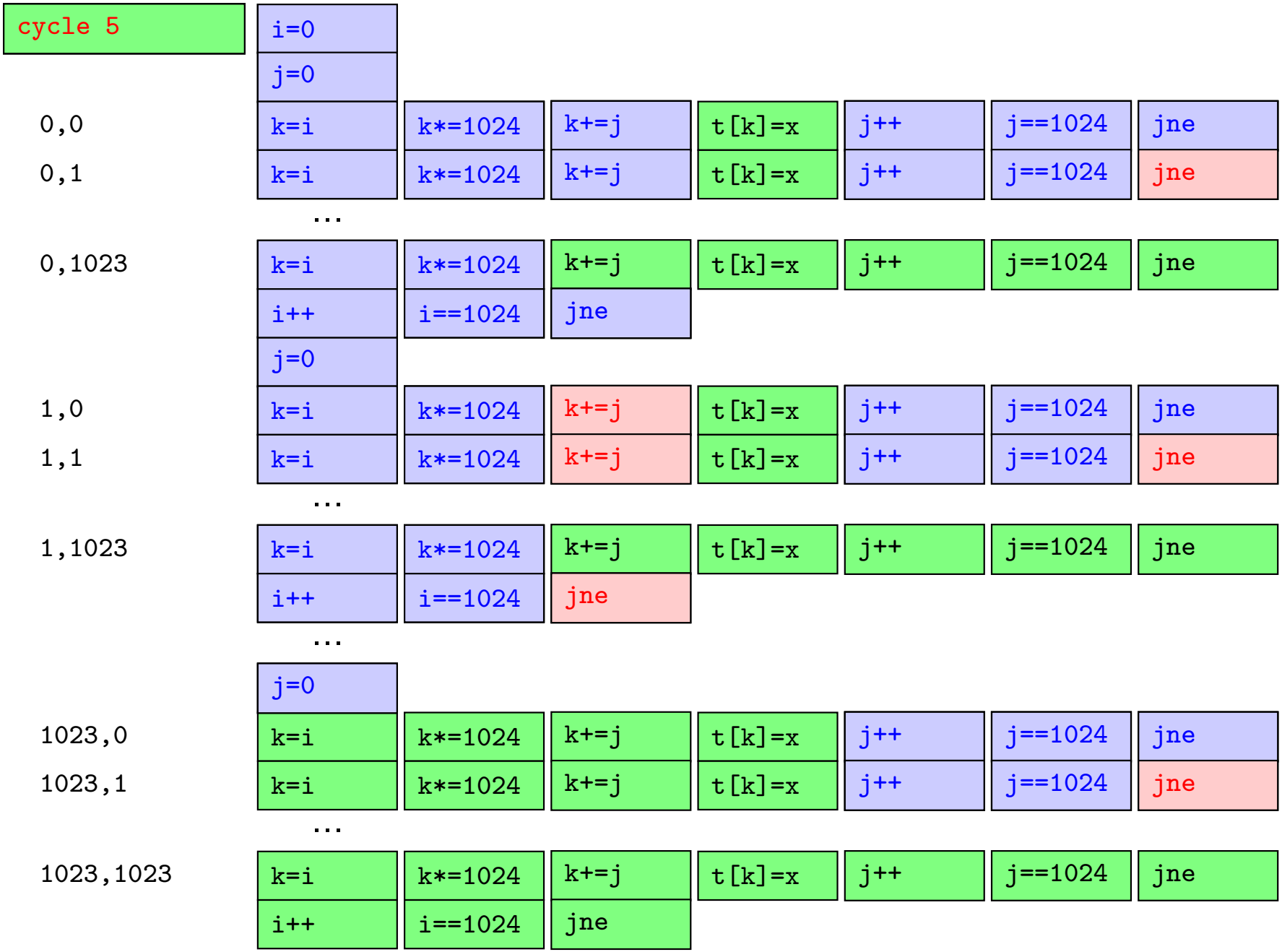

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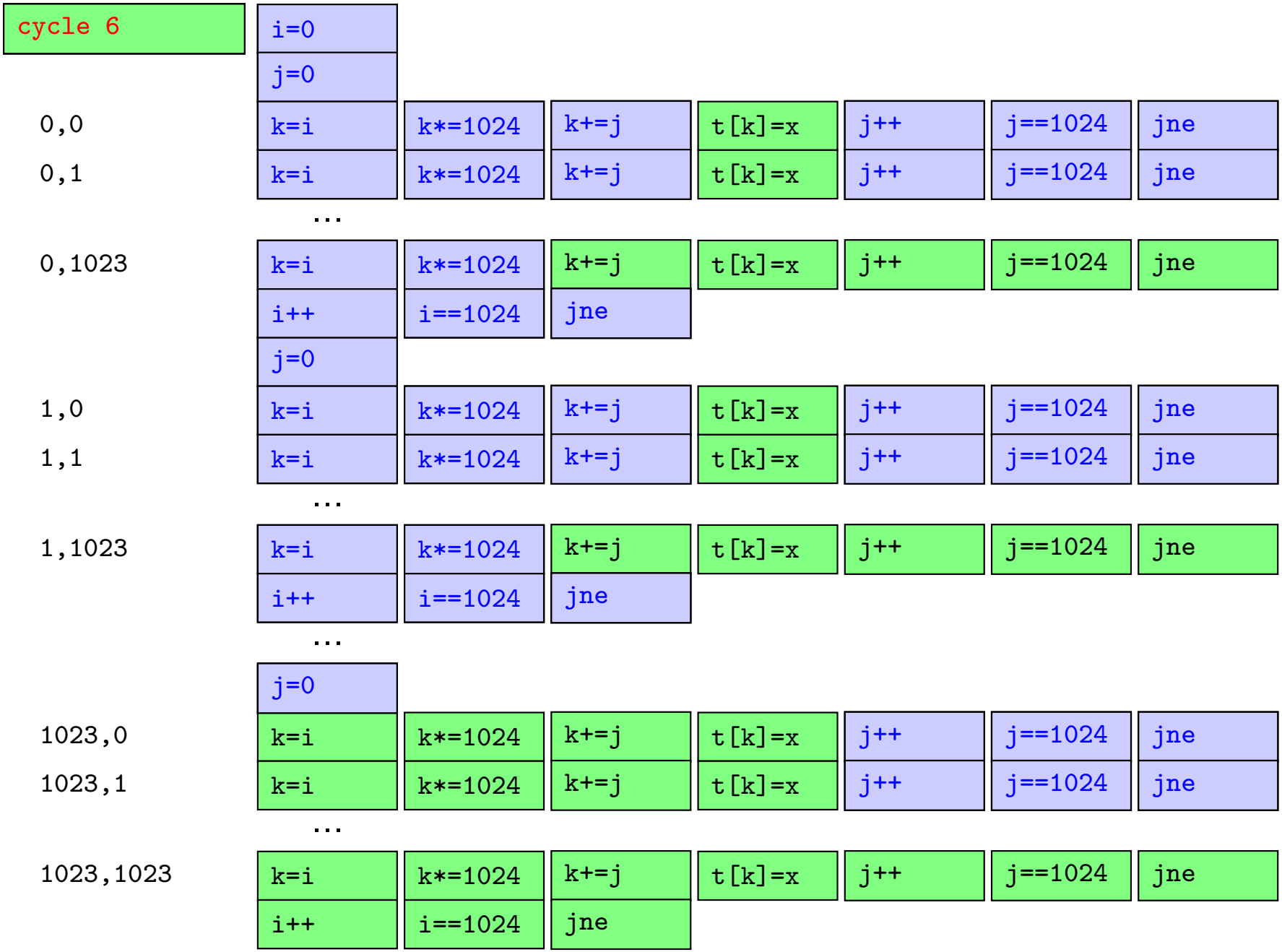

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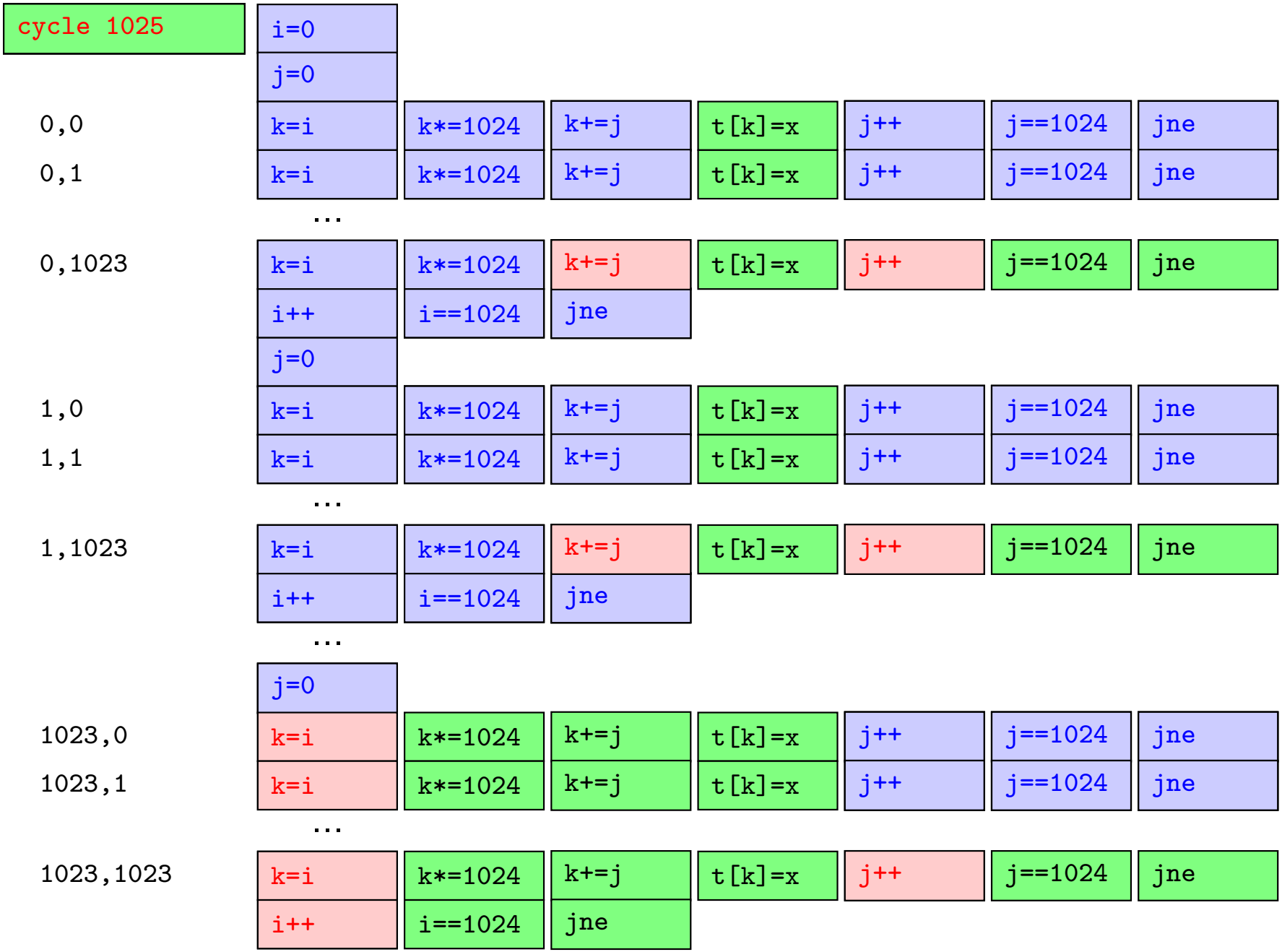

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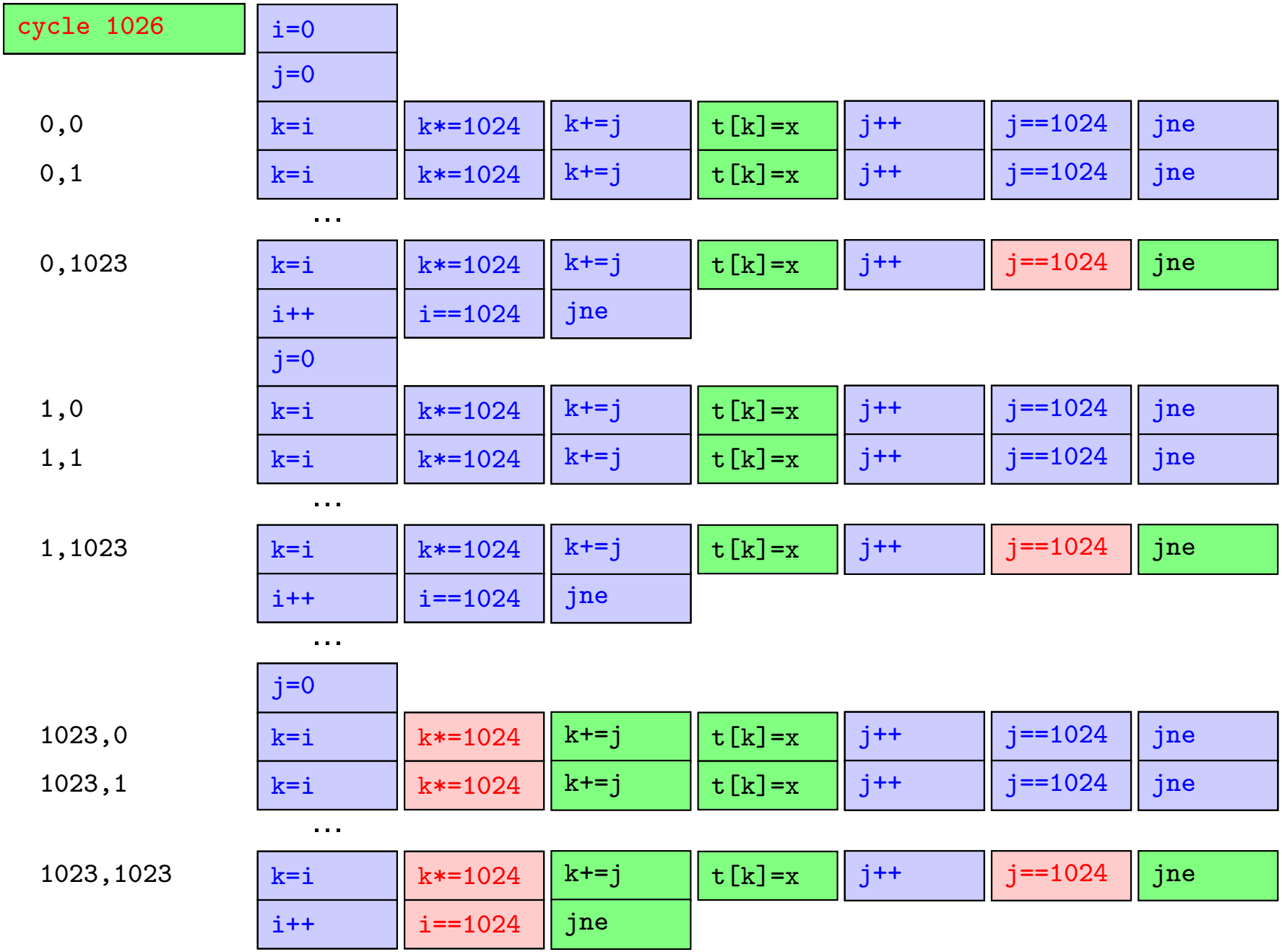

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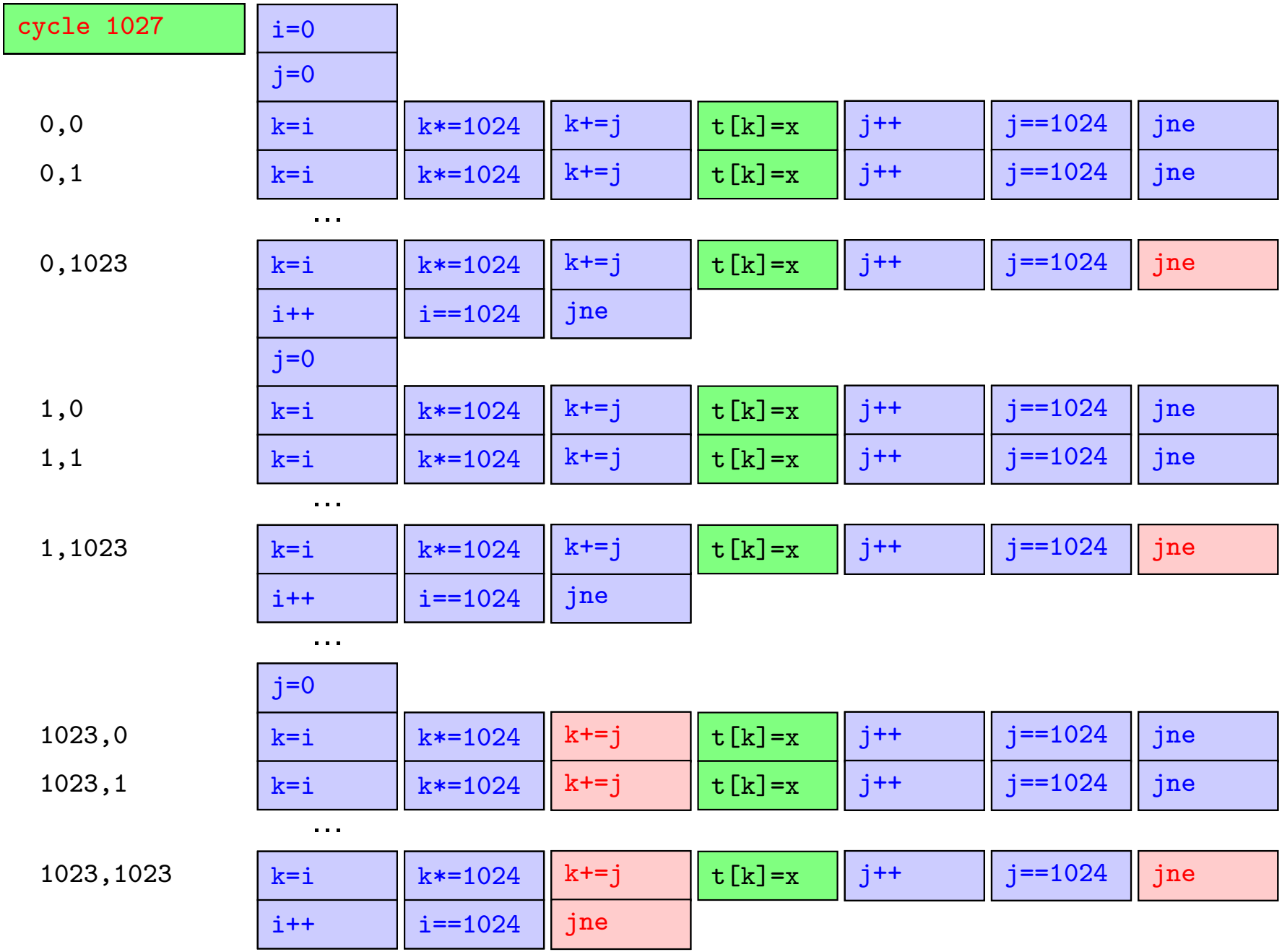

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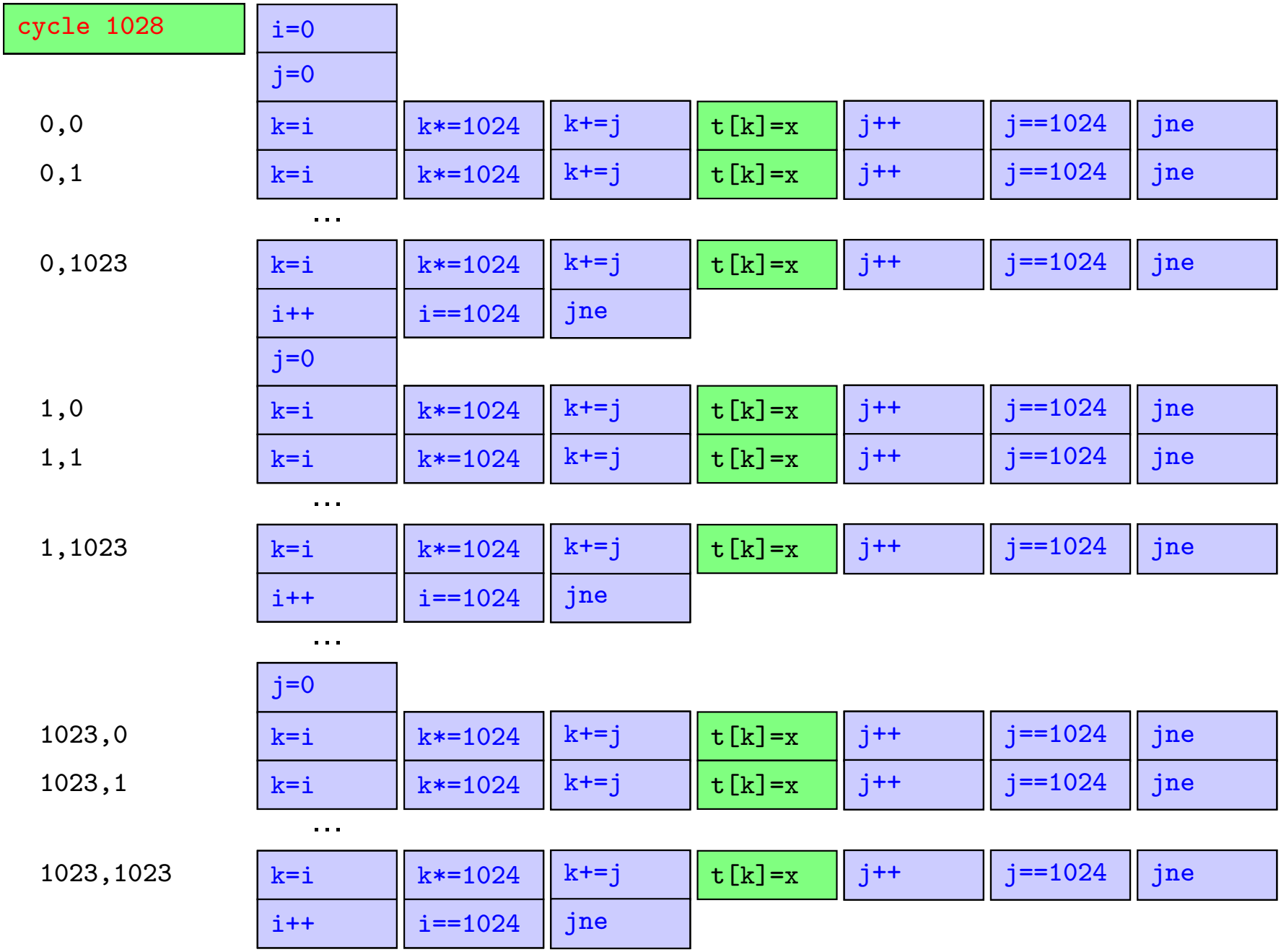

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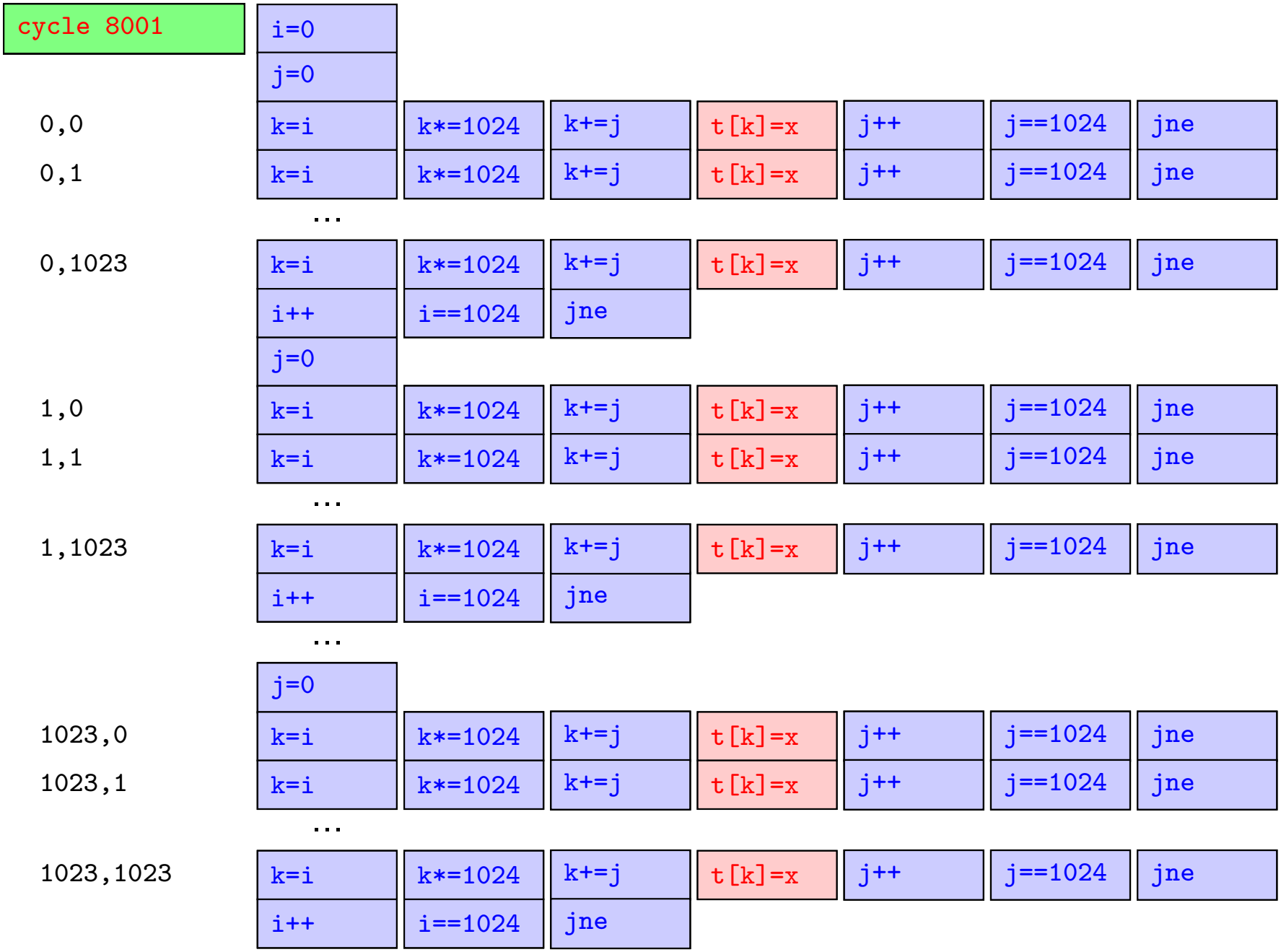

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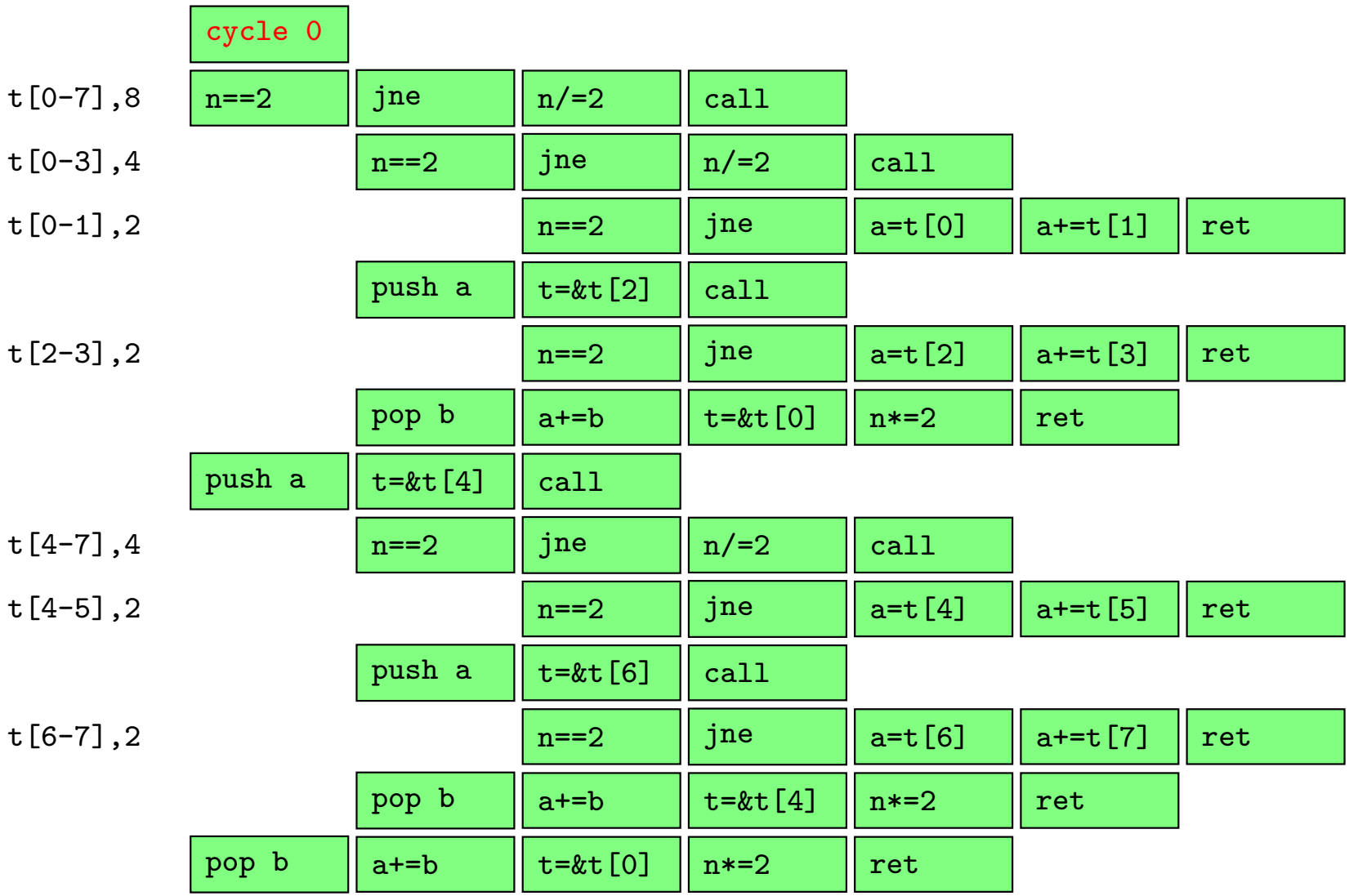
Running sum_reduce(t[0,7],8) in parallel.



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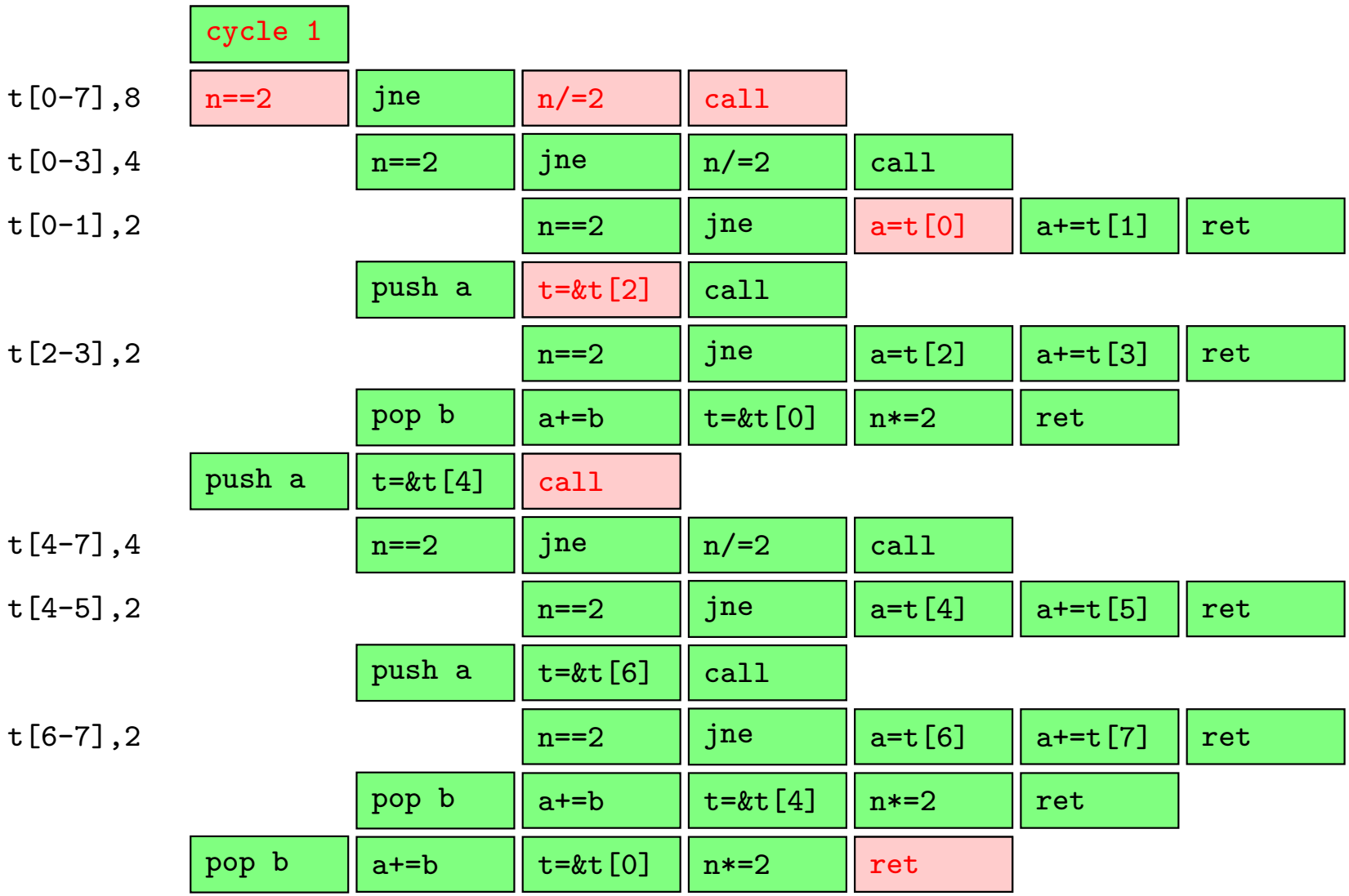

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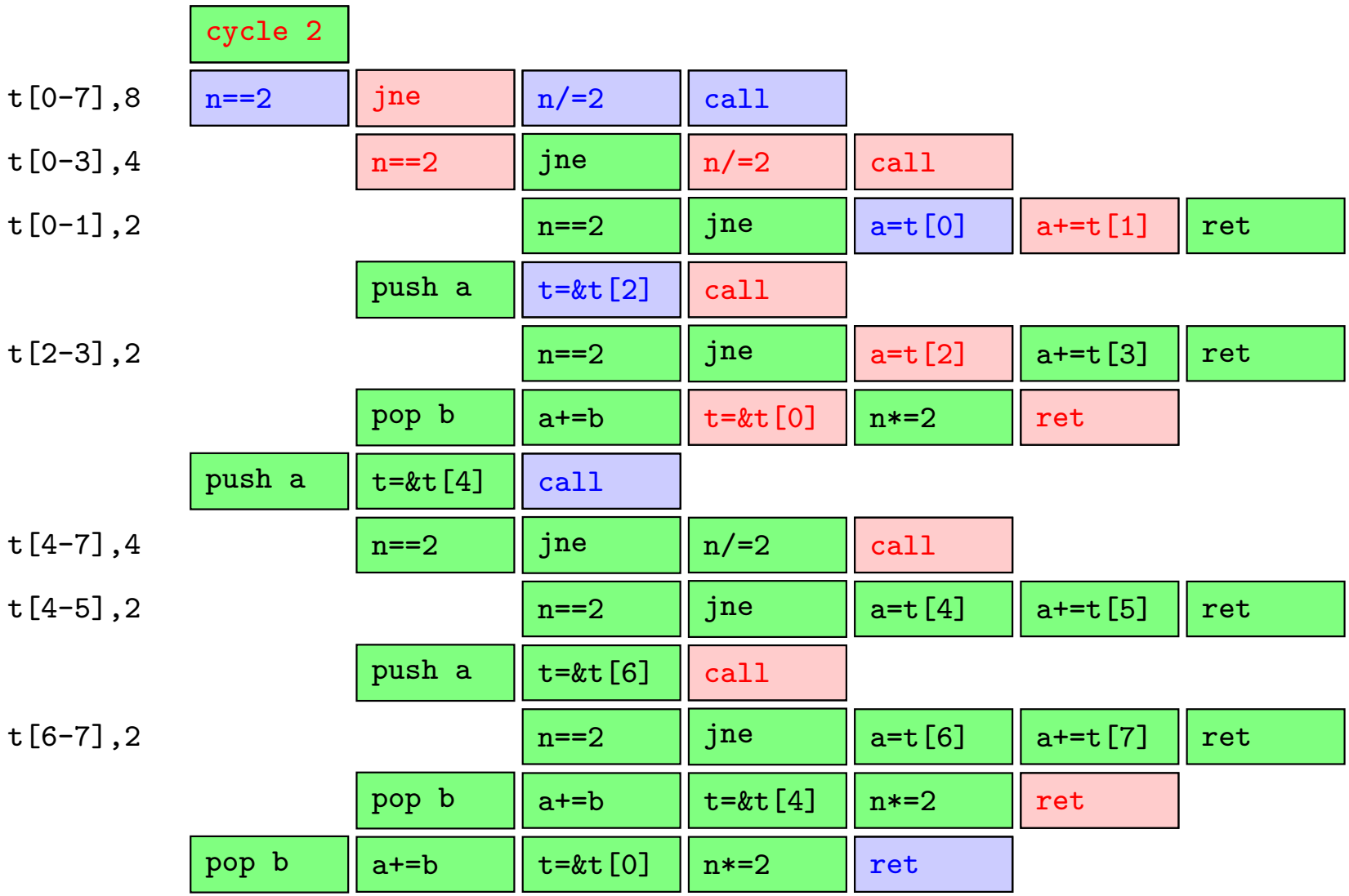

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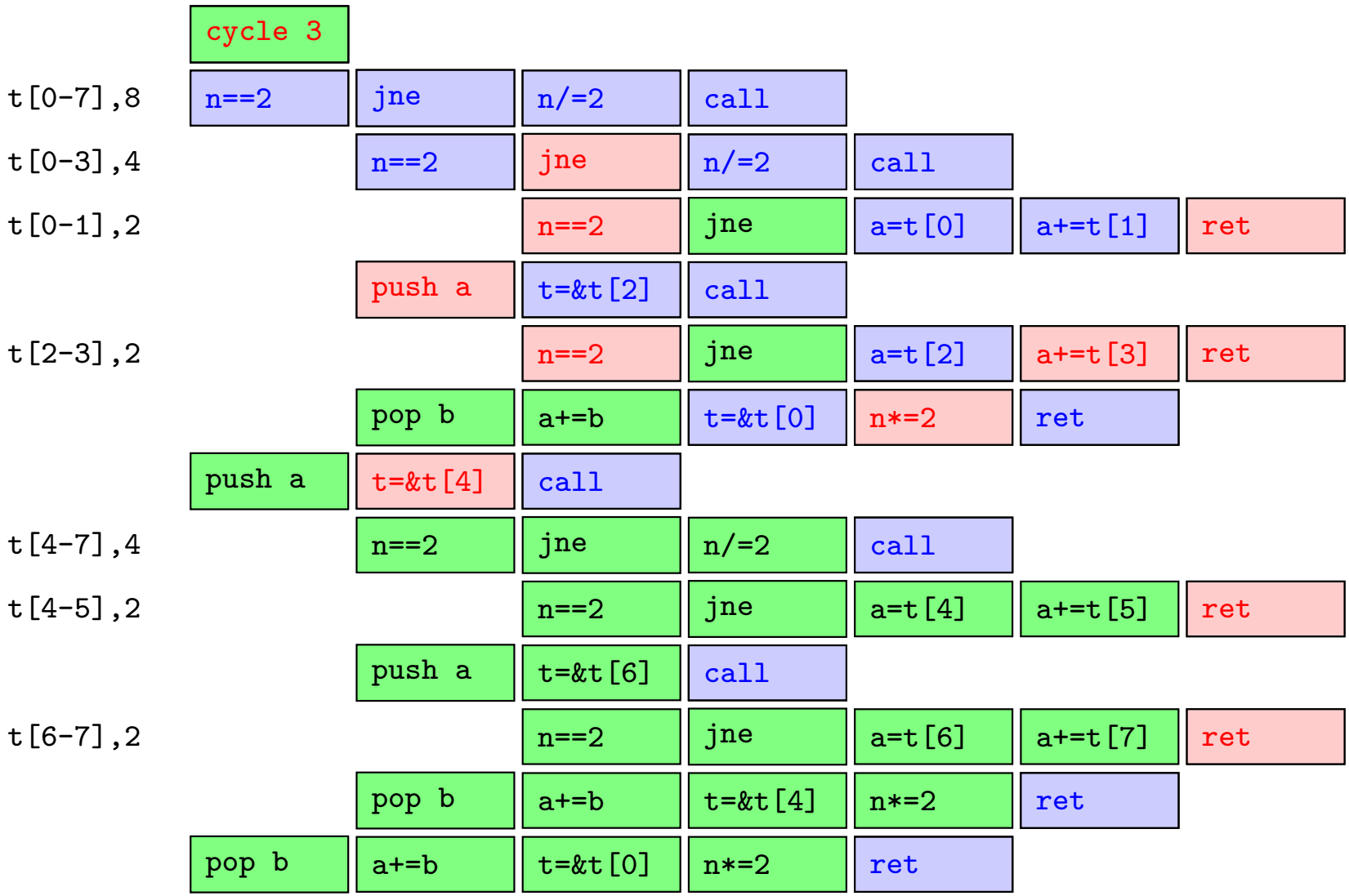

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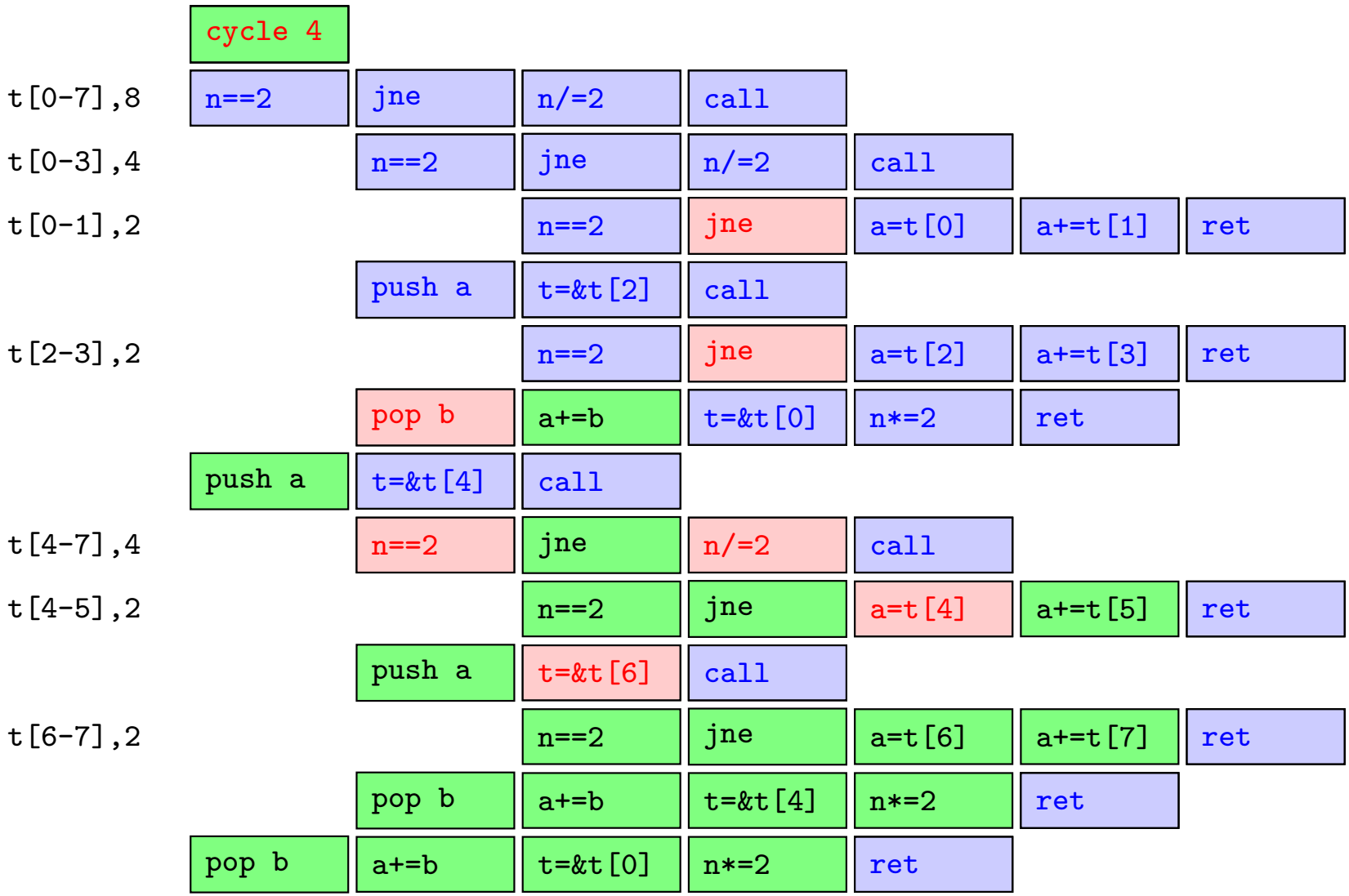

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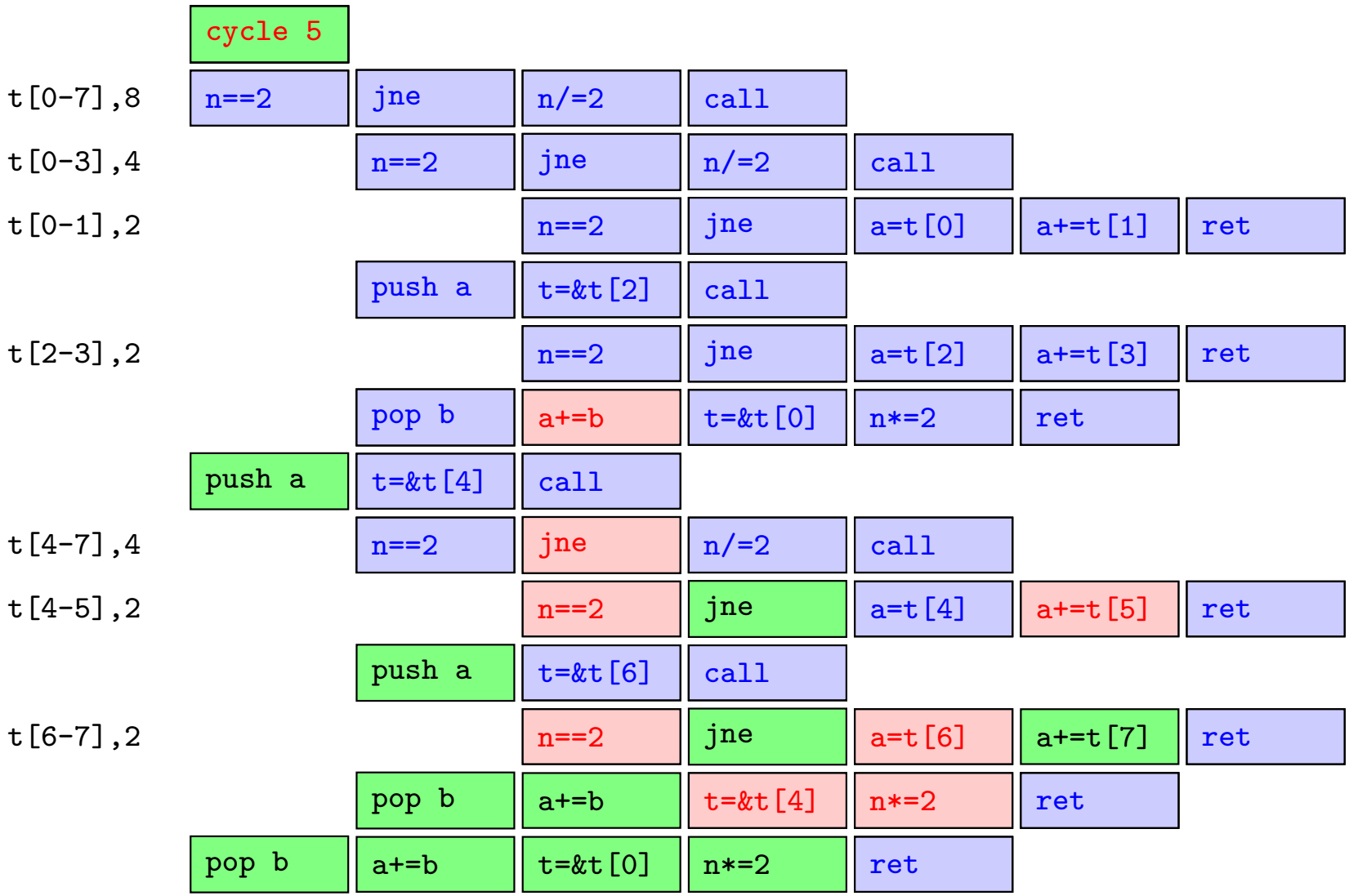

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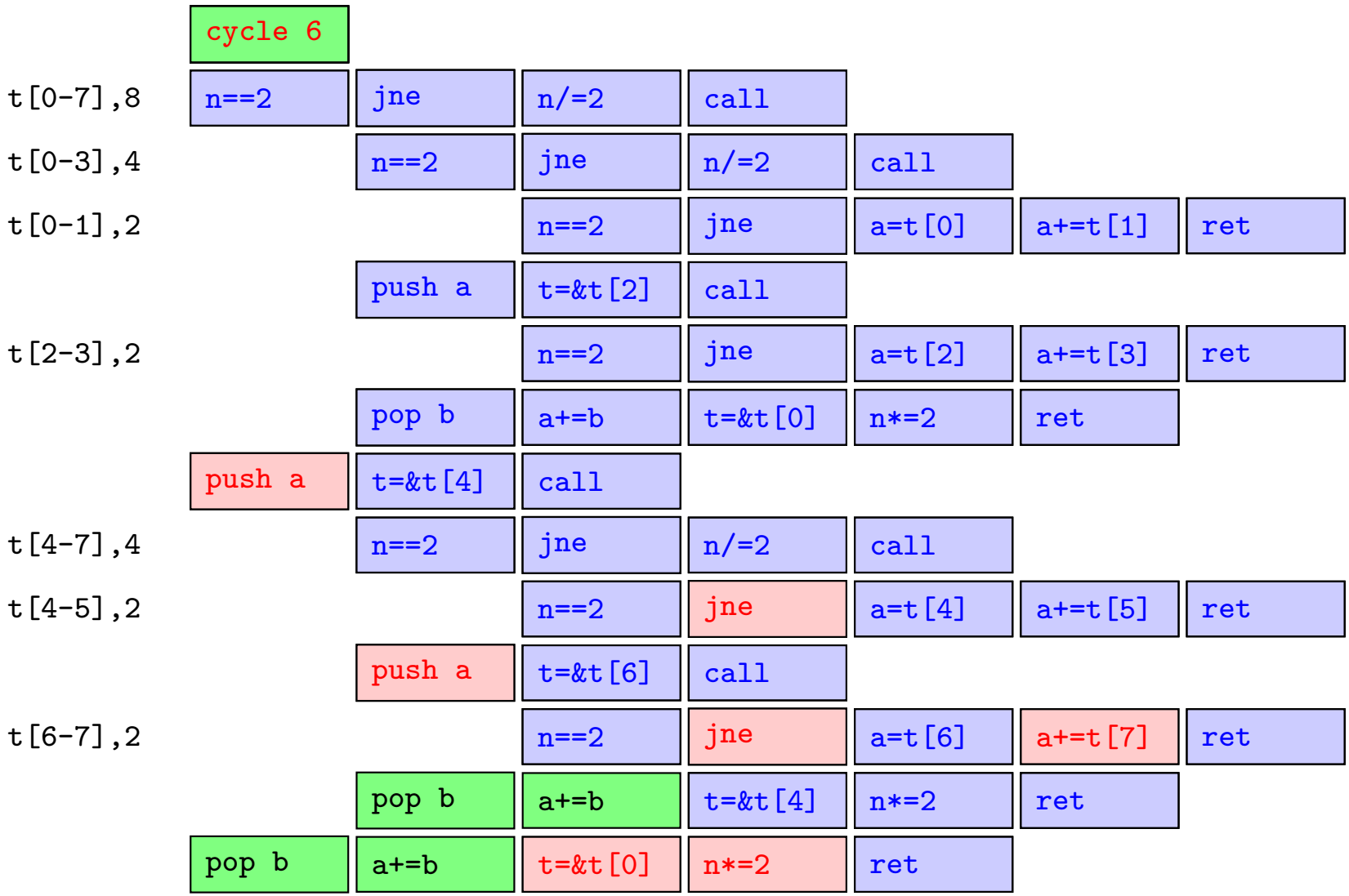

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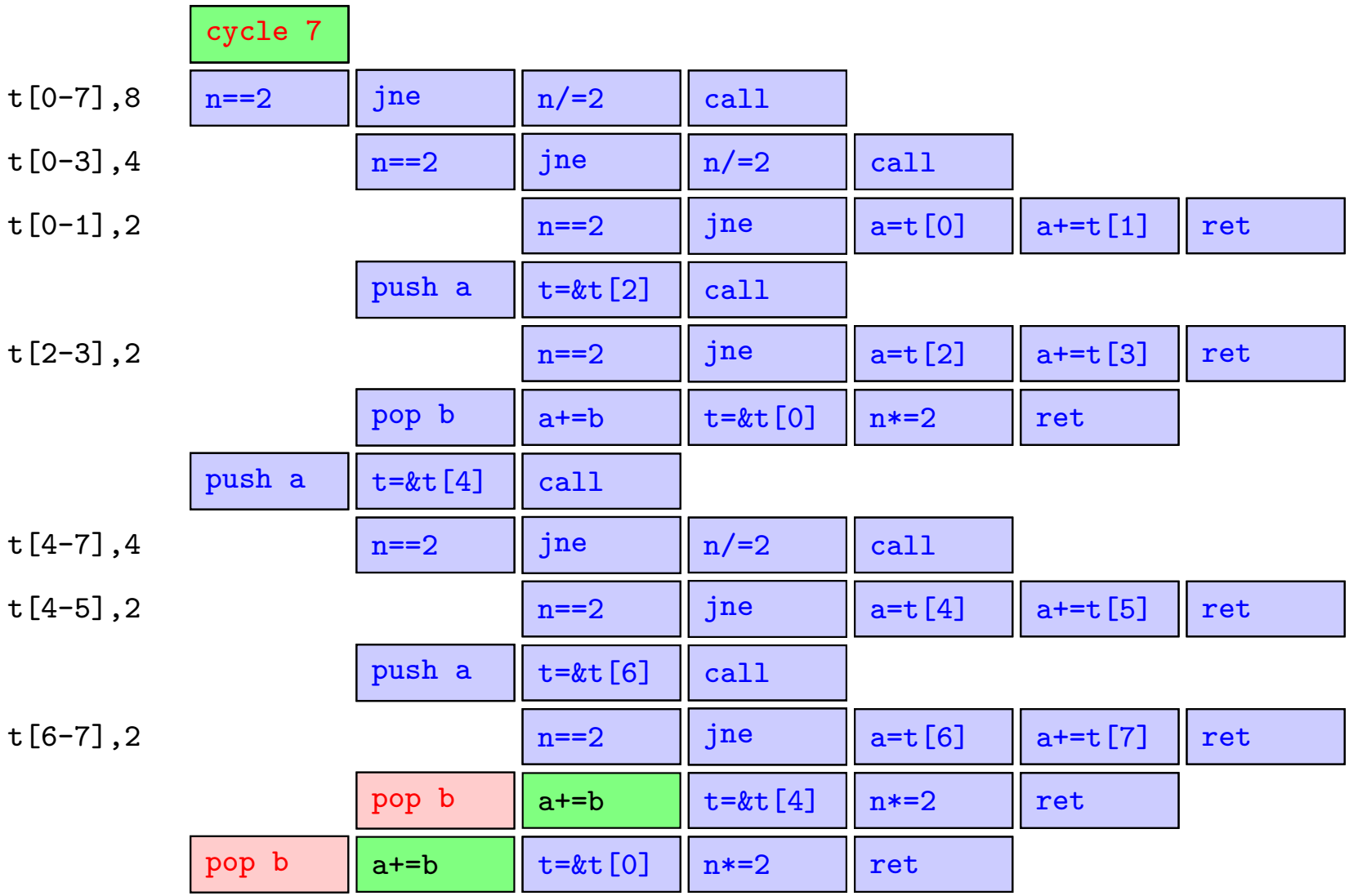

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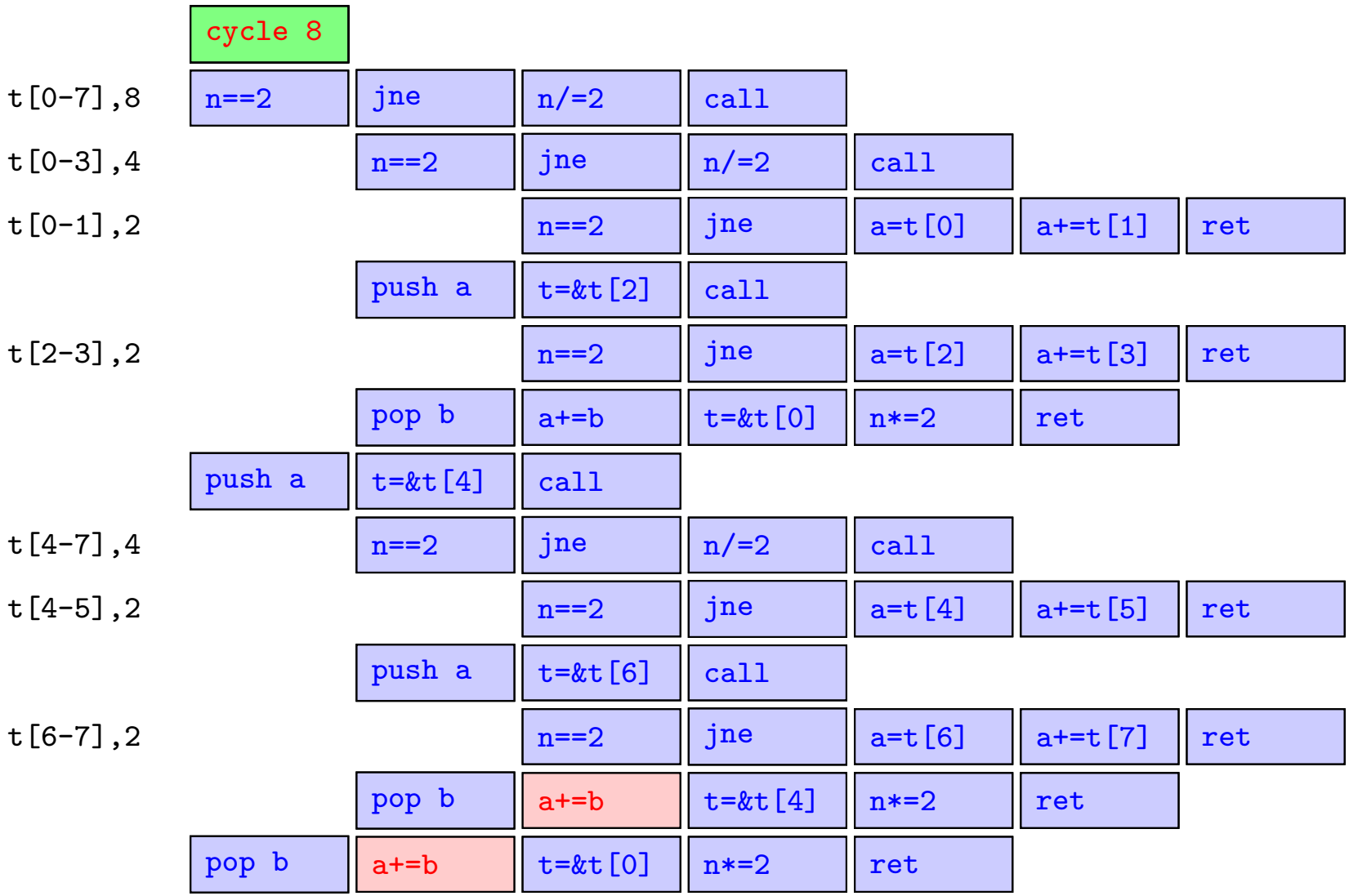

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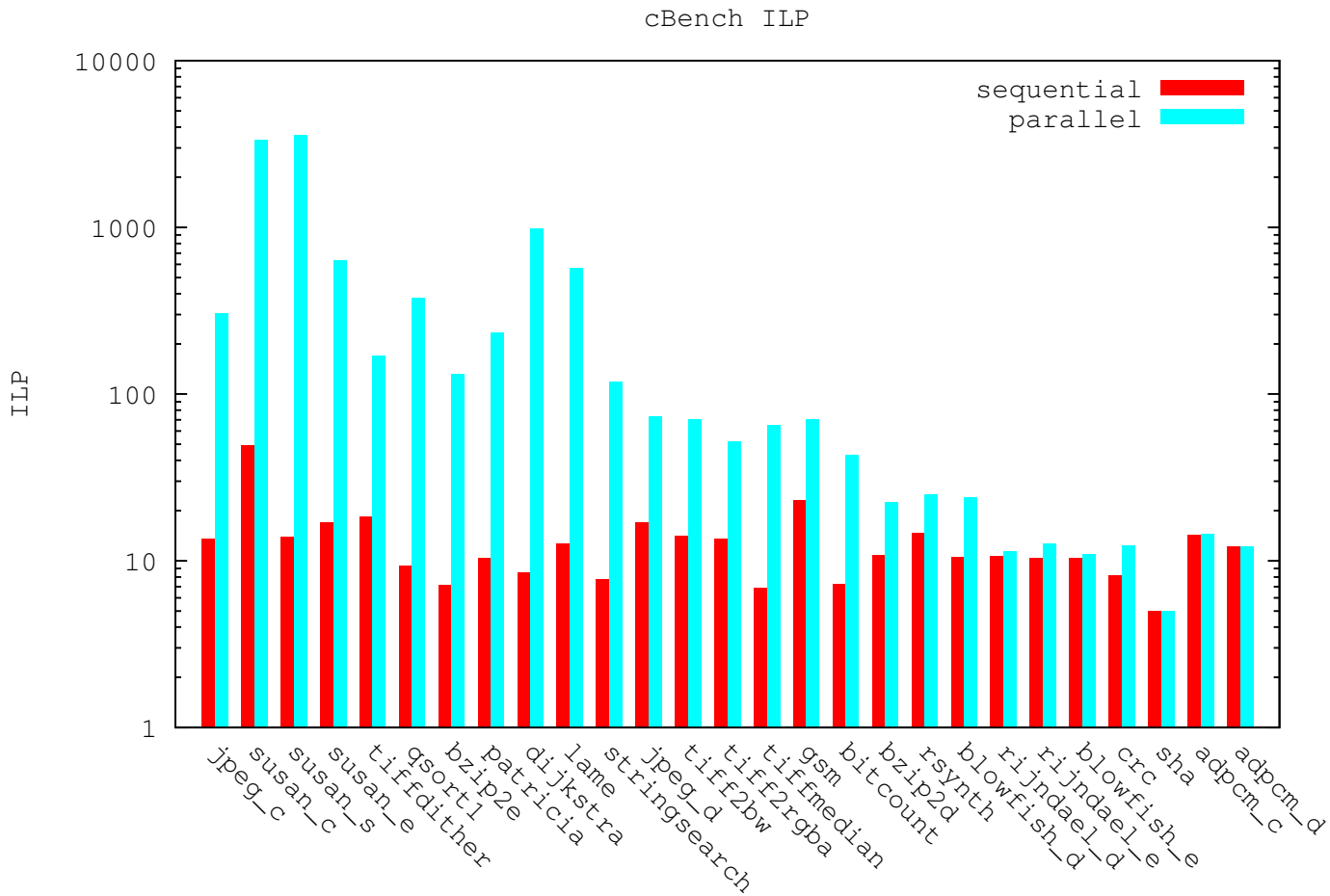
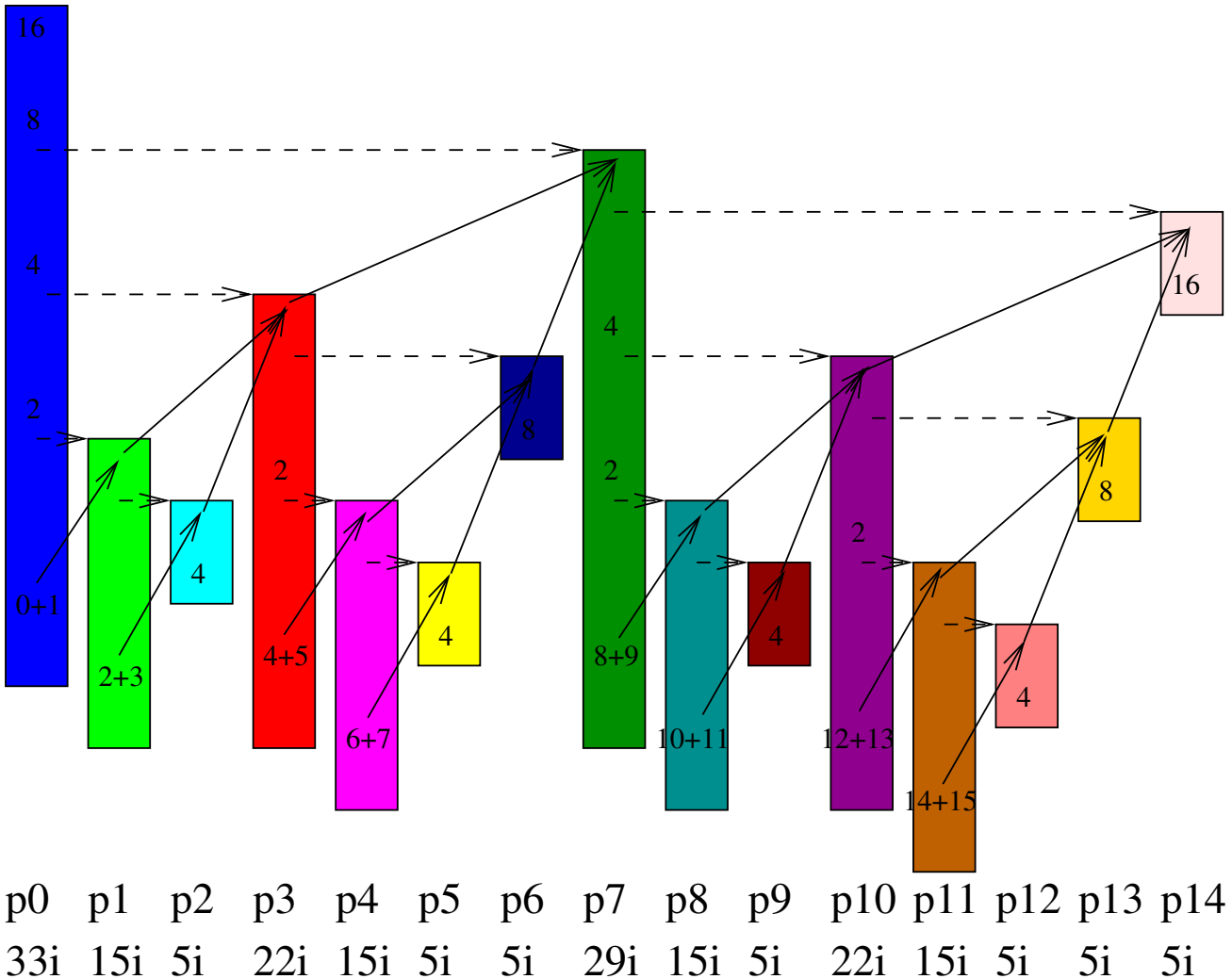
- Optionally, by renaming constants we can precompute loop control at rename phase to allow vectorization at run phase.

Impact de la parallélisation de l'extraction, du renommage et de l'exécution.

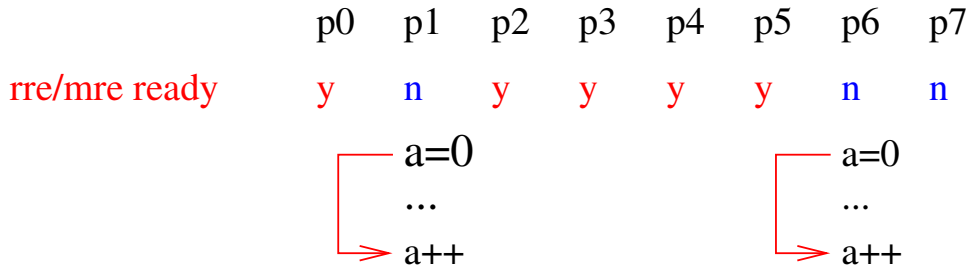


Le modèle d'exécution parallèle appliqué à sum_reduce(t,16).



Le renommage en parallèle.

(a) parallel local imports



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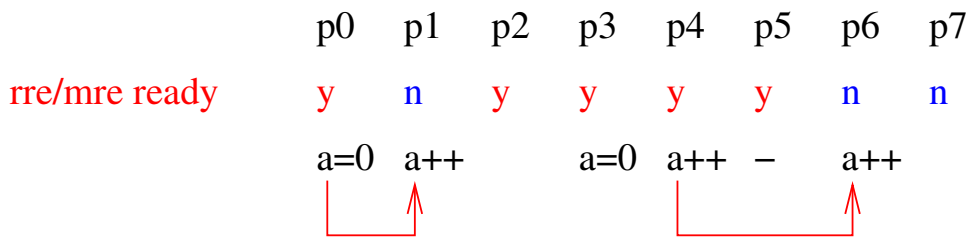
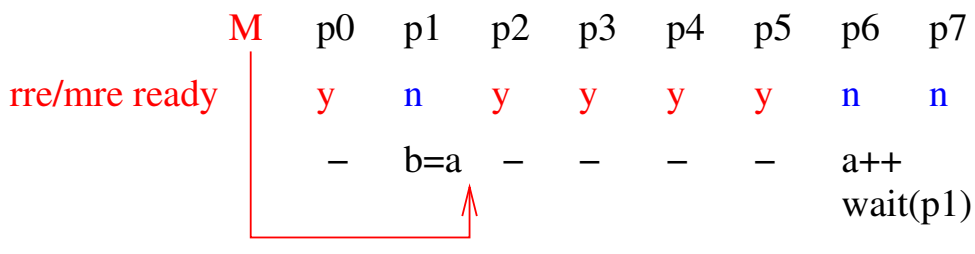
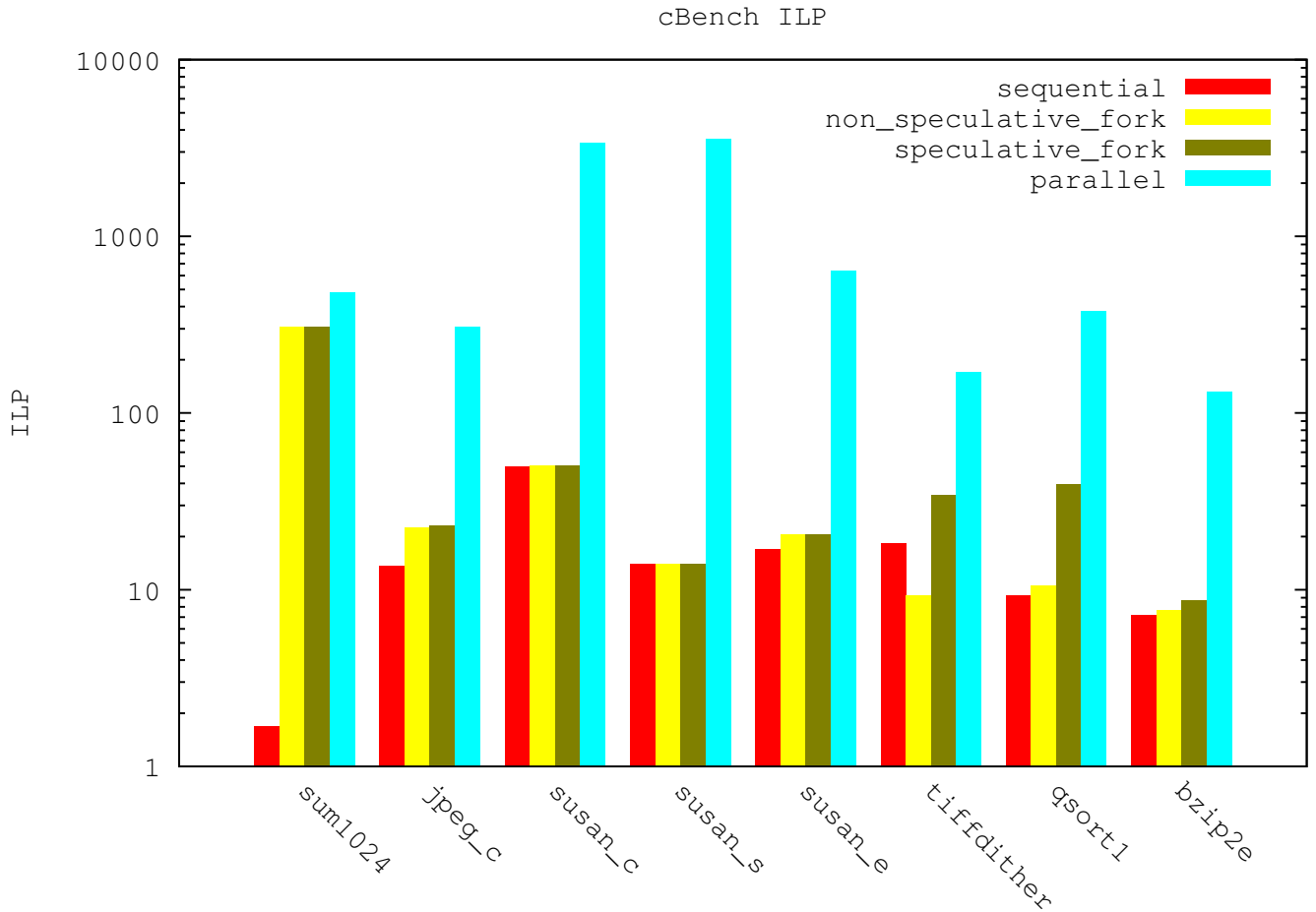


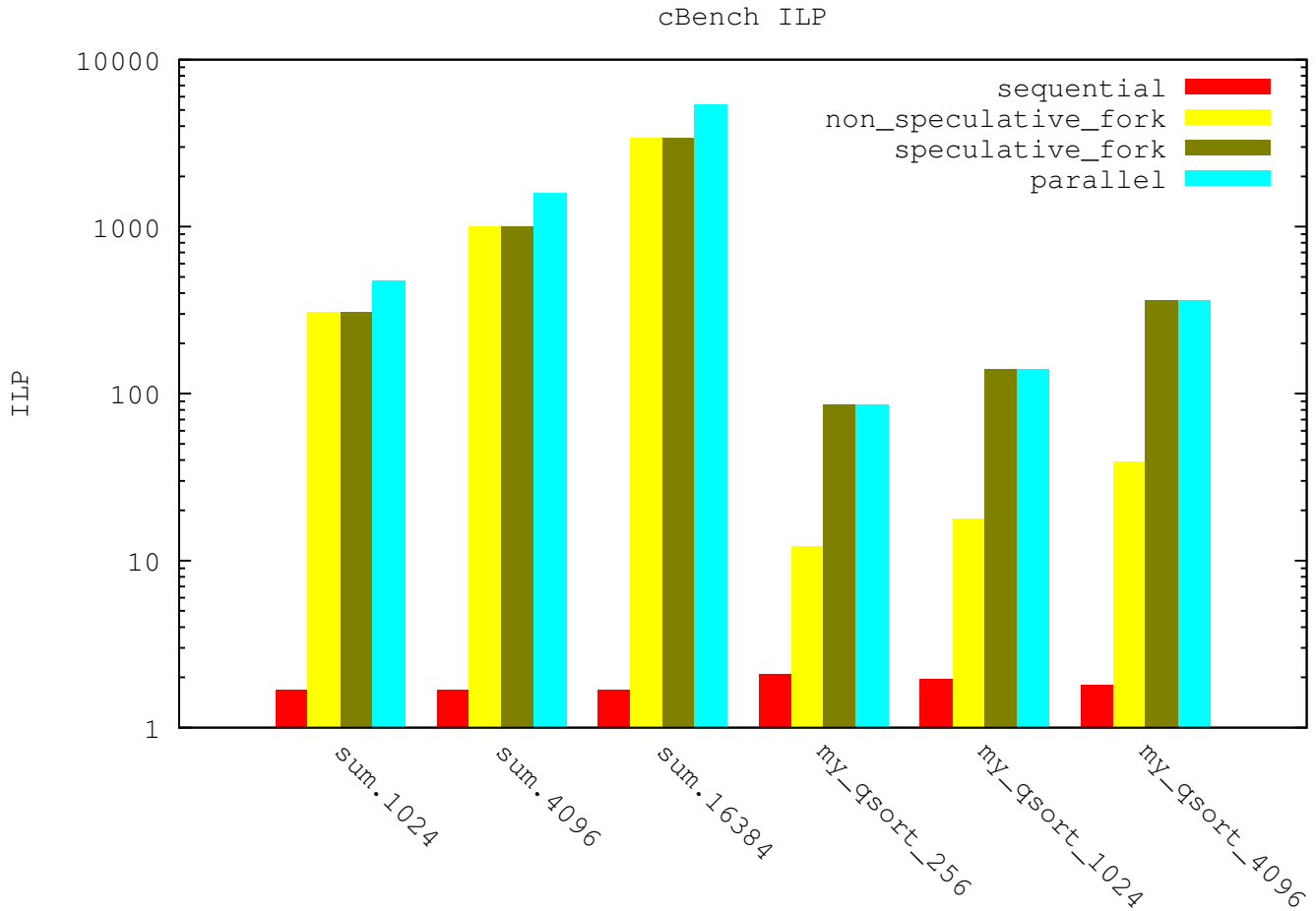
(c) memory import and import wait



La capture d'ILP avec fork spéculatif et non spéculatif.



La capture d'ILP sur deux algorithmes parallèles.



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- What we usually call sequential programs contain a lot of parallelism unless the algorithms they come from are themselves sequential.