软件分析

南京大学

计算机科学与技术系

程序设计语言与静态分析研究组

李樾 谭添

Static Program Analysis

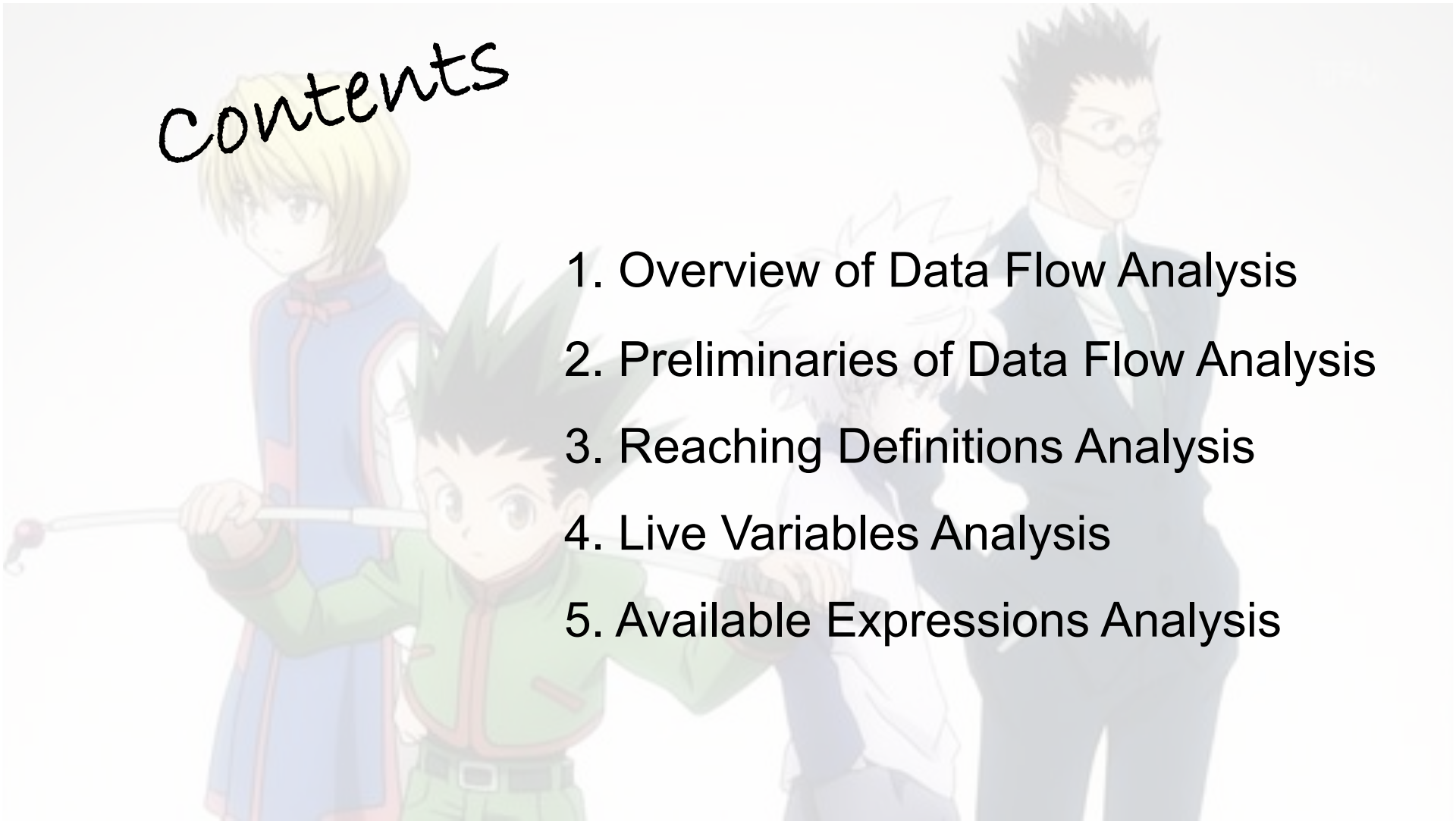
Data Flow Analysis — Applications

Nanjing University

Yue Li

2022

Contents



Data Flow Analysis

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How Data Flows on CFG?

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How application-specific Data Flows through the Nodes (BBs/statements) and Edges (control flows) of CFG (a program)?

Recall 1st lecture

Data Flow Analysis

How Data Flows on CFG?

How application-specific Data ← Abstraction

Over-approximation → Flows through the

Nodes (BBs/statements) and

Edges (control flows) of

CFG (a program)?

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for most static analyses (may analysis)

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for most static analyses (may analysis)

may analysis:
outputs information that may be true (over-approximation)
must analysis:
outputs information that must be true (under-approximation)
Over- and under-approximations are both for safety of analysis

Data Flow Analysis

How Data Flows on CFG?

How application-specific Data ← Abstraction

Safe-approximation → Flows through the

may analysis: safe=over

must analysis: safe=under

Nodes (BBs/statements) and

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Data Flow Analysis

How Data Flows on CFG?

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different data-flow analysis applications have
different data abstraction and
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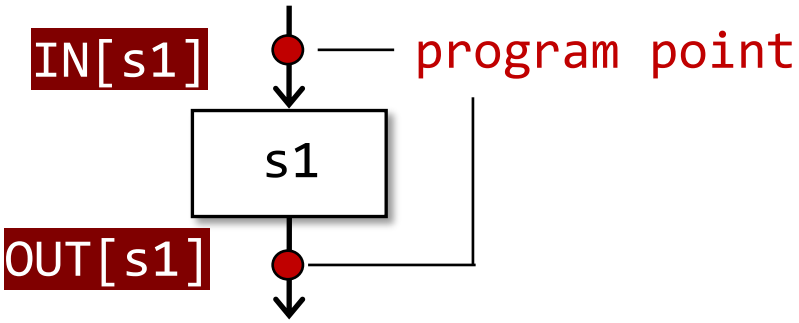
Preliminaries of Data Flow Analysis

Input and Output States

- Each execution of an IR statement transforms an input state to a new output state
- The input (output) state is associated with the program point before (after) the statement



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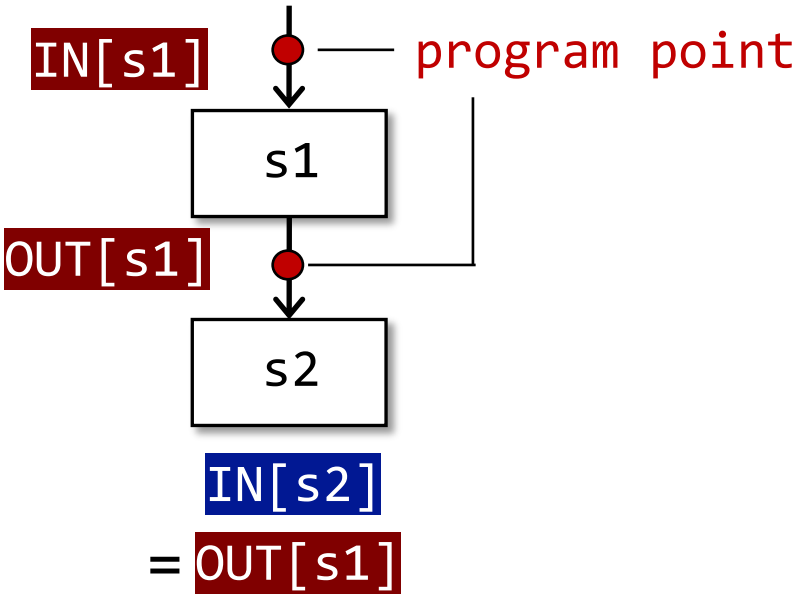

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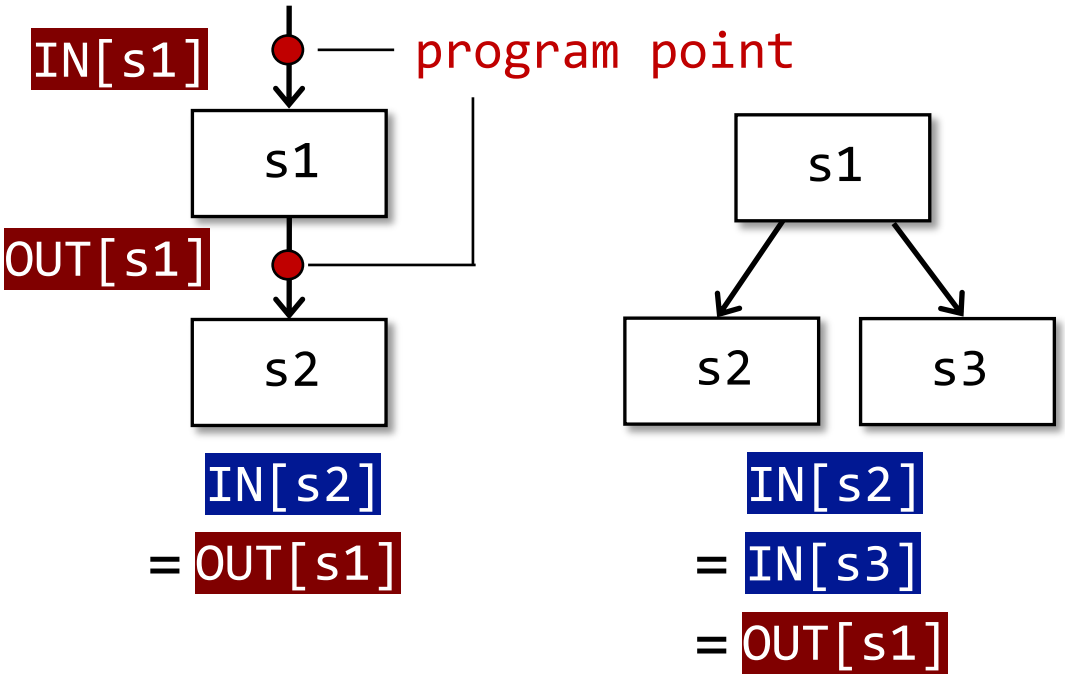

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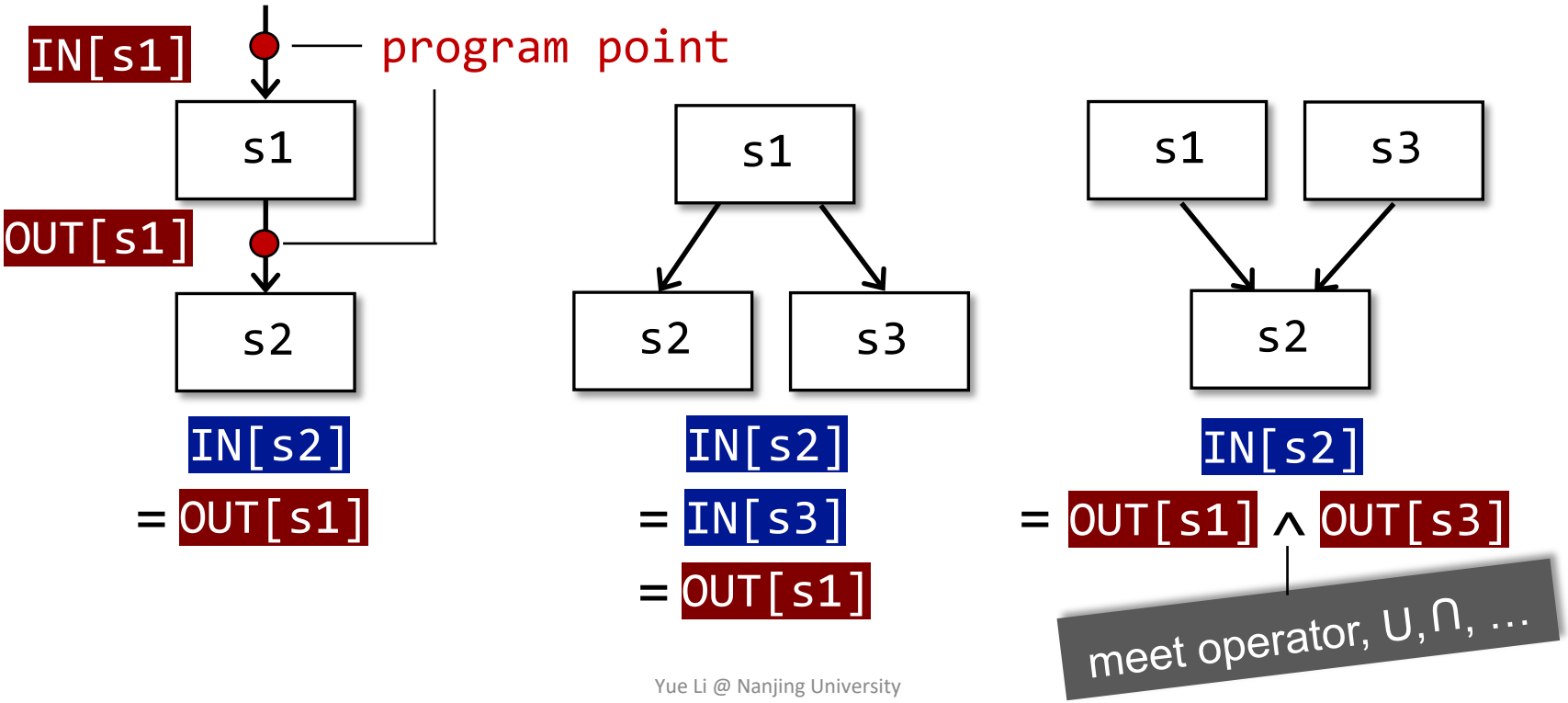

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Recall 1st lecture

```
x = 10;
  ●
y = -1;
  ●
x = y;
  ●
x = x / 6;
  ●
```

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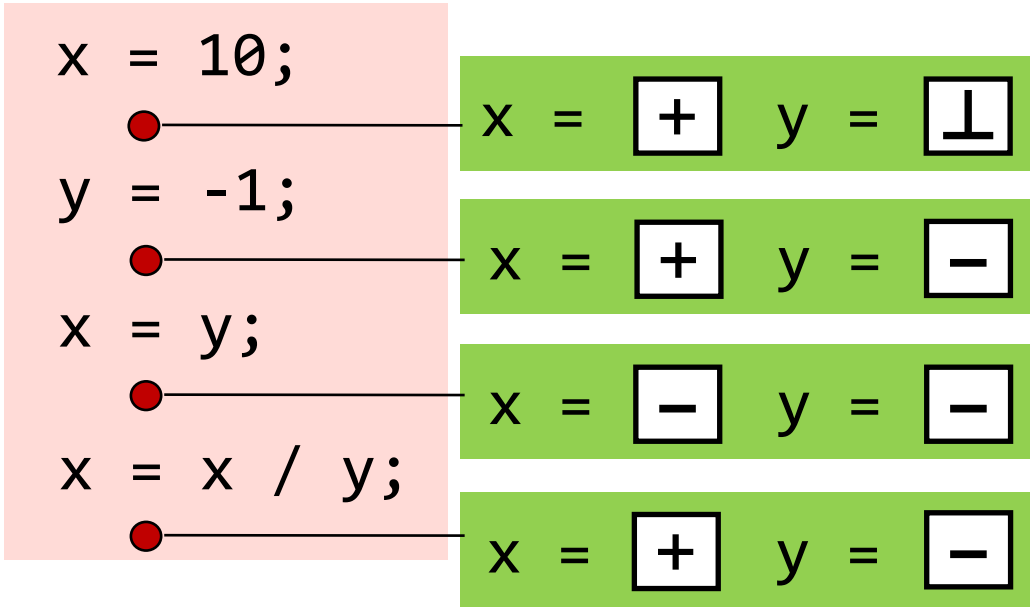

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x = + y = −

x = − y = −

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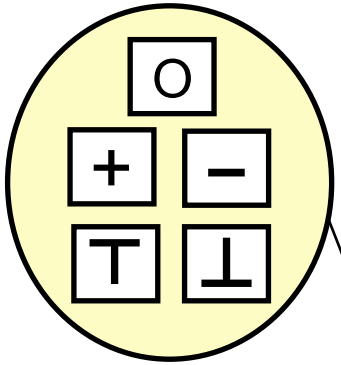

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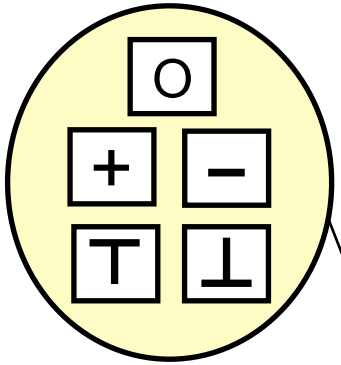

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The set of possible data-flow values is the domain for this application

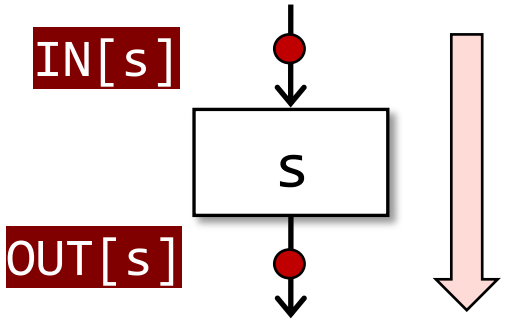
Data-flow analysis is to find a solution to a set of *safe-approximation-directed constraints* on the IN[s]'s and OUT[s]'s, for all statements s.

- *constraints* based on semantics of statements (*transfer functions*)
- *constraints* based on the *flows of control*

Notations for Transfer Function's Constraints

- Forward Analysis

$$\mathrm{OUT}[s] = f_s(\mathrm{IN}[s])$$



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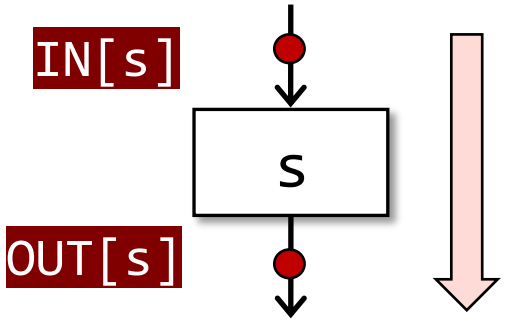
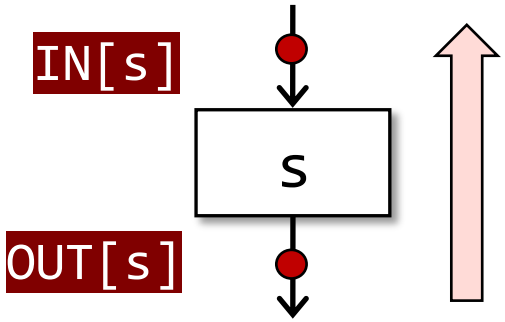


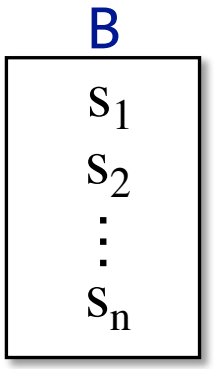
- Backward Analysis

$$\mathrm{IN}[s] = f_s(\mathrm{OUT}[s])$$



Notations for Control Flow's Constraints

- Control flow within a BB



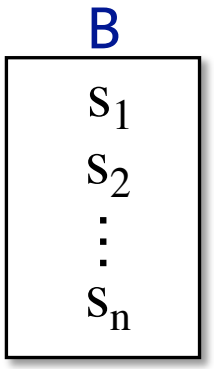
- Control flow among BBs

Notations for Control Flow's Constraints

- Control flow within a BB

$$\mathrm{IN}[s_{i+1}] = \mathrm{OUT}[s_i],\ \textit{for all } i = 1, 2, \ldots, n\text{-}1$$

- Control flow among BBs



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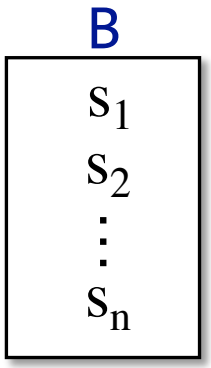


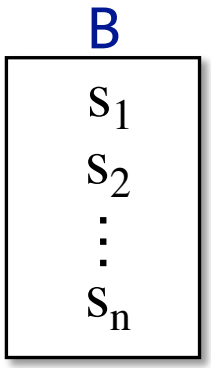
- Control flow among BBs

$$\mathrm{IN}[B] = \mathrm{IN}[s_1] \qquad \mathrm{OUT}[B] = \mathrm{OUT}[s_n]$$

Notations for Control Flow's Constraints

- Control flow within a BB

$$\text{IN}[s_{i+1}] = \text{OUT}[s_i],\ \textit{for all}\ i = 1, 2, \ldots, \text{n-1}$$



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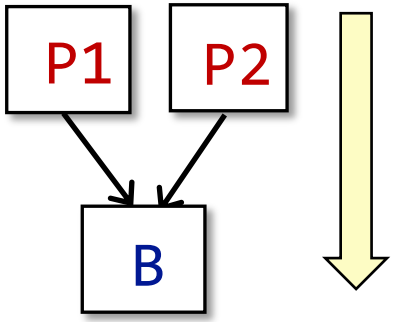
$$\text{IN}[B] = \text{IN}[s_1] \qquad \text{OUT}[B] = \text{OUT}[s_n]$$

$$\text{OUT}[B] = f_B(\text{IN}[B]),\ f_B = f_{s_n} \circ \ldots \circ f_{s_2} \circ f_{s_1}$$

$$\text{IN}[B] = \bigwedge_{P \text{ a predecessor of } B} \text{OUT}[P]$$



The meet operator $\wedge$ is used to summarize the contributions from different paths at the confluence of those paths

Notations for Control Flow's Constraints

- Control flow within a BB

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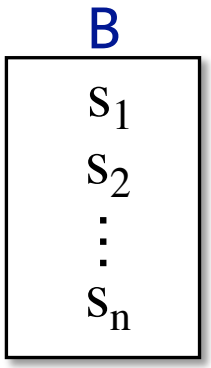

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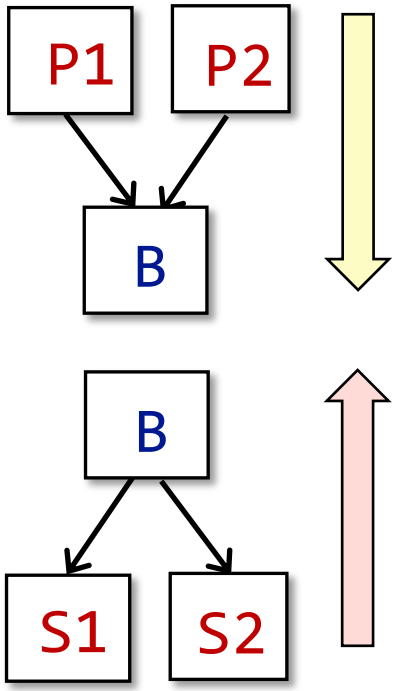
$$\text{OUT}[B] = \bigwedge S \text{ a successor of } B\ \text{IN}[S]$$



Data Flow Analysis Applications

(I) Reaching Definitions Analysis

(II) Live Variables Analysis

(III) Available Expressions Analysis

Issues Not Covered

- Method Calls

  - Intra-procedural CFG

  - Will be introduced in lecture: Inter-procedural Analysis

- Aliases

  - Variables have no aliases

  - Will be introduced in lecture: Pointer Analysis

Reaching Definitions

A definition d at program point p *reaches* a point q if there is a path from p to q such that d is not "killed" along that path

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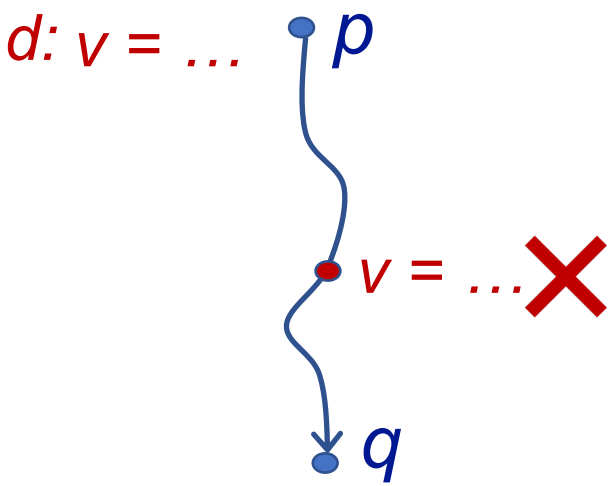

Reaching Definitions

A definition d at program point p *reaches* a point q if there is a path from p to q such that d is not "killed" along that path

- A definition of a variable v is a statement that assigns a value to v
- Translated as: definition of variable v at program point p reaches point q if there is a path from p to q such that no new definition of v appears on that path
- Reaching definitions can be used to detect possible undefined variables. e.g., introduce a dummy definition for each variable v at the entry of CFG, and if the dummy definition of v reaches a point p where v is used, then v may be used before definition (as *undefined* reaches v)

Understanding Reaching Definitions

Abstraction

- Data Flow Values/Facts

  - The definitions of all the variables in a program

Understanding Reaching Definitions

Abstraction

- Data Flow Values/Facts
  - The definitions of all the variables in a program
  - Can be represented by bit vectors

e.g., D1, D2, D3, D4, …, D100 (100 definitions)

00000…0

100 bits

Bit i from the left represents definition Di

Understanding Reaching Definitions

Safe-approximation

- Transfer Function

- Control Flow

Understanding Reaching Definitions

```
D: v = x op y
```

Safe-approximation

This statement "generates" a definition D of variable v and "kills" all the other definitions in the program that define variable v, while leaving the remaining incoming definitions unaffected.

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- Control Flow

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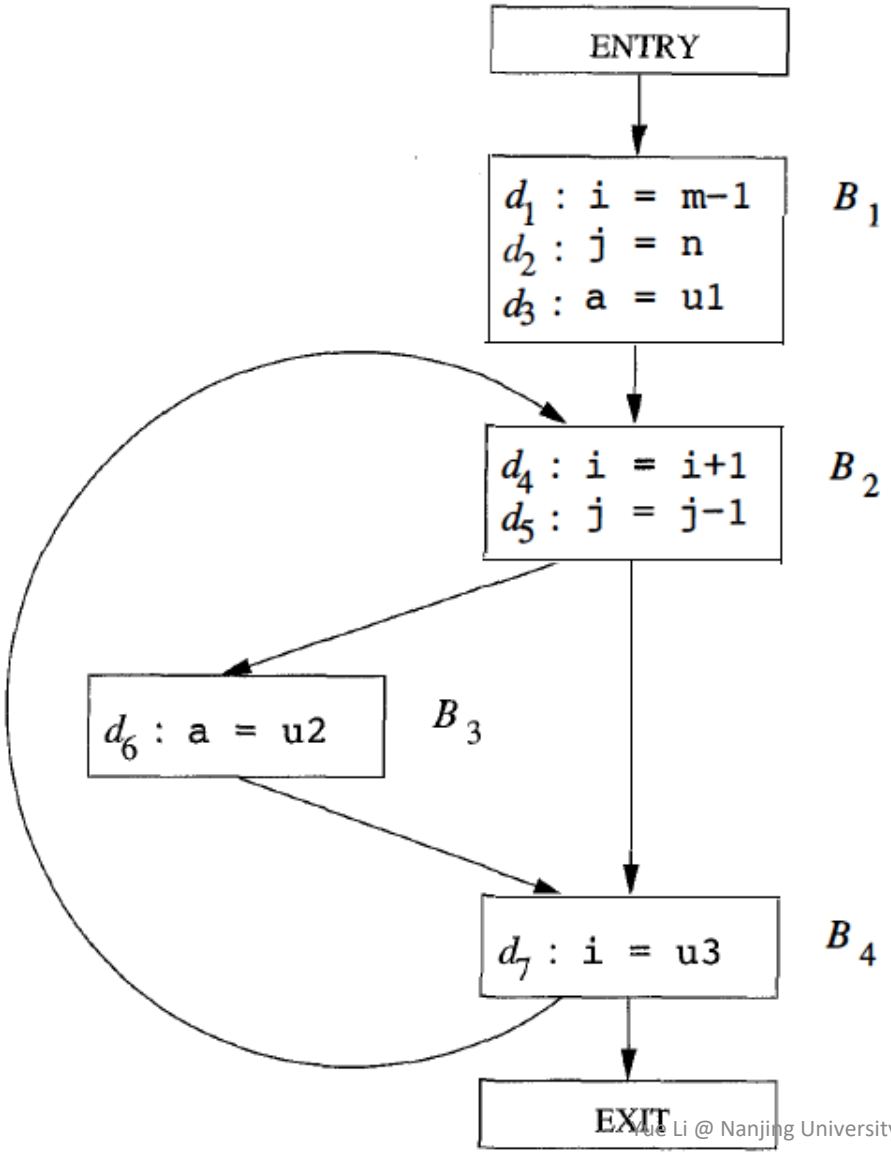

$gen_{B_1} = \{ d_1, d_2, d_3 \}$

$kill_{B_1} = \{ d_4, d_5, d_6, d_7 \}$

$gen_{B_2} = \{ d_4, d_5 \}$

$kill_{B_2} = \{ d_1, d_2, d_7 \}$

$gen_{B_3} = \{ d_6 \}$

$kill_{B_3} = \{ d_3 \}$

$gen_{B_4} = \{ d_7 \}$

$kill_{B_4} = \{ d_1, d_4 \}$

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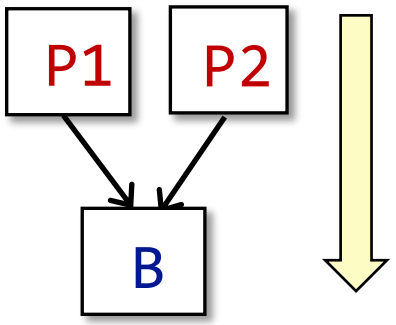

Understanding Reaching Definitions

Safe-approximation

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A definition reaches a program point as long as there exists at least one path along which the definition reaches.

- Control Flow

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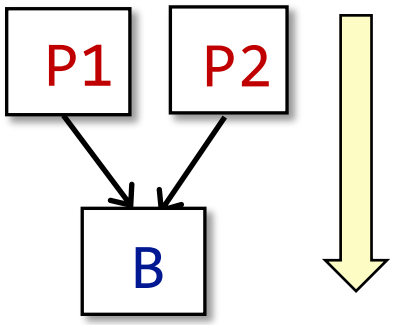

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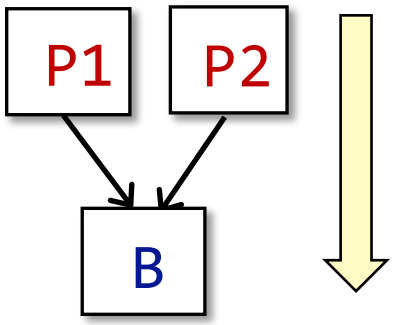


Algorithm of Reaching Definitions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

OUT[*entry*] = ∅;
for (each basic block *B**entry*)
    OUT[*B*] = ∅;
while (changes to any OUT occur)
    for (each basic block *B**entry*) {
        IN[*B*] = $\bigcup_{P \text{ a predecessor of } B}$ OUT[*P*];
        OUT[*B*] = gen_B U (IN[*B*] - $kill_B$);
    }

Algorithm of Reaching Definitions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

OUT[*entry*] = ∅; ?

for (each basic block $B \backslash entry$)

    OUT[B] = ∅;

while (changes to any OUT occur)

    for (each basic block $B \backslash entry$) {

        IN[B] = $\bigcup_{P \text{ a predecessor of } B}$ OUT[P];

        OUT[B] = $gen_B \cup (\text{IN}[B] - kill_B)$;

    }

Algorithm of Reaching Definitions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

```
OUT[entry] = ∅;
for (each basic block B\entry) ?
    OUT[B] = ∅;
 while (changes to any OUT occur)
    for (each basic block B\entry) {
        IN[B] = U_{P a predecessor of B} OUT[P];
        OUT[B] = gen_B U (IN[B] - kill_B);
    }
```

Why entry is excluded?

Algorithm of Reaching Definitions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

OUT[*entry*] = ∅;
for (each basic block *B**entry*)
    OUT[*B*] = ∅; ?
while (changes to any OUT occur)
    for (each basic block *B**entry*) {
        IN[*B*] = $\bigcup_{P \text{ a predecessor of } B}$ OUT[*P*];
        OUT[*B*] = gen_B U (IN[*B*] - $kill_B$);
    }

Algorithm of Reaching Definitions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

Why this iterative algorithm can finally stop?

```
OUT[entry] = ∅;
for (each basic block B\entry)
    OUT[B] = ∅;
while (changes to any OUT occur) ?
    for (each basic block B\entry) {
        IN[B] = ∪_{P a predecessor of B} OUT[P];
        OUT[B] = gen_B ∪ (IN[B] - kill_B);
    }
```

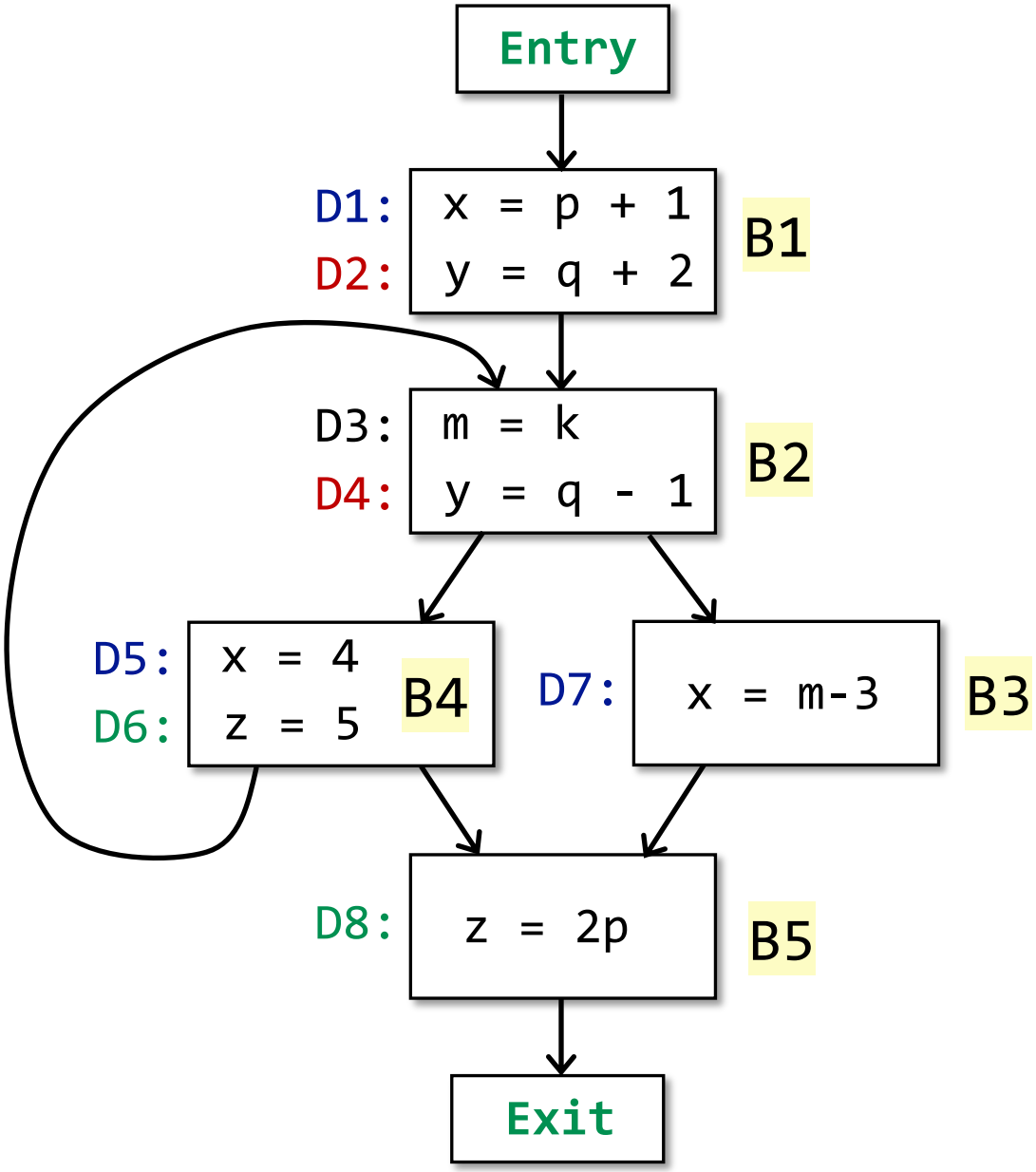
Algorithm of Reaching Definitions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

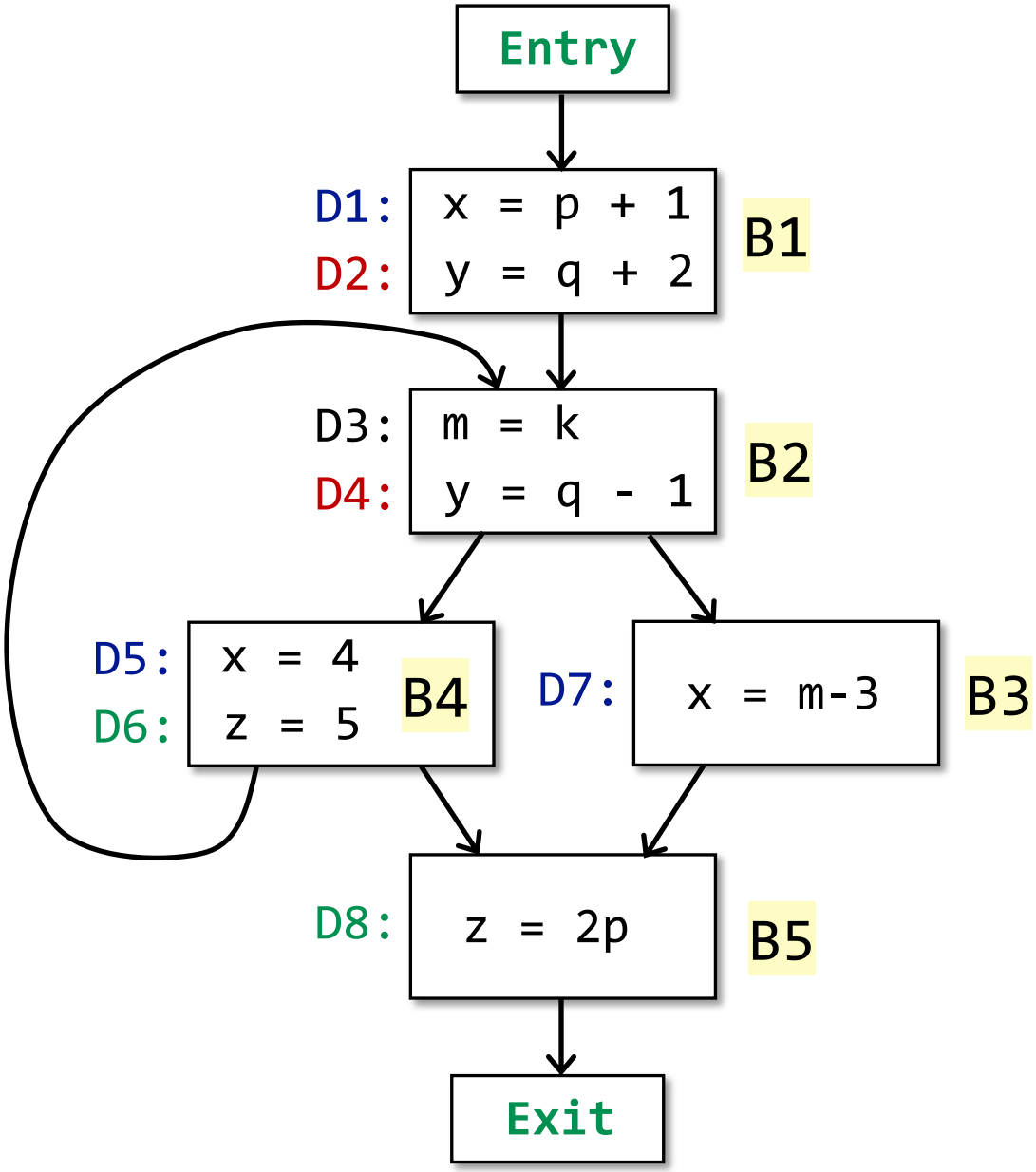
OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

OUT[*entry*] = ∅;
for (each basic block *B**entry*)
    OUT[*B*] = ∅;
while (changes to any OUT occur)
    for (each basic block *B**entry*) {
        IN[*B*] = $\bigcup_{P \text{ a predecessor of } B}$ OUT[*P*];
        OUT[*B*] = gen_B U (IN[*B*] - $kill_B$);
    }

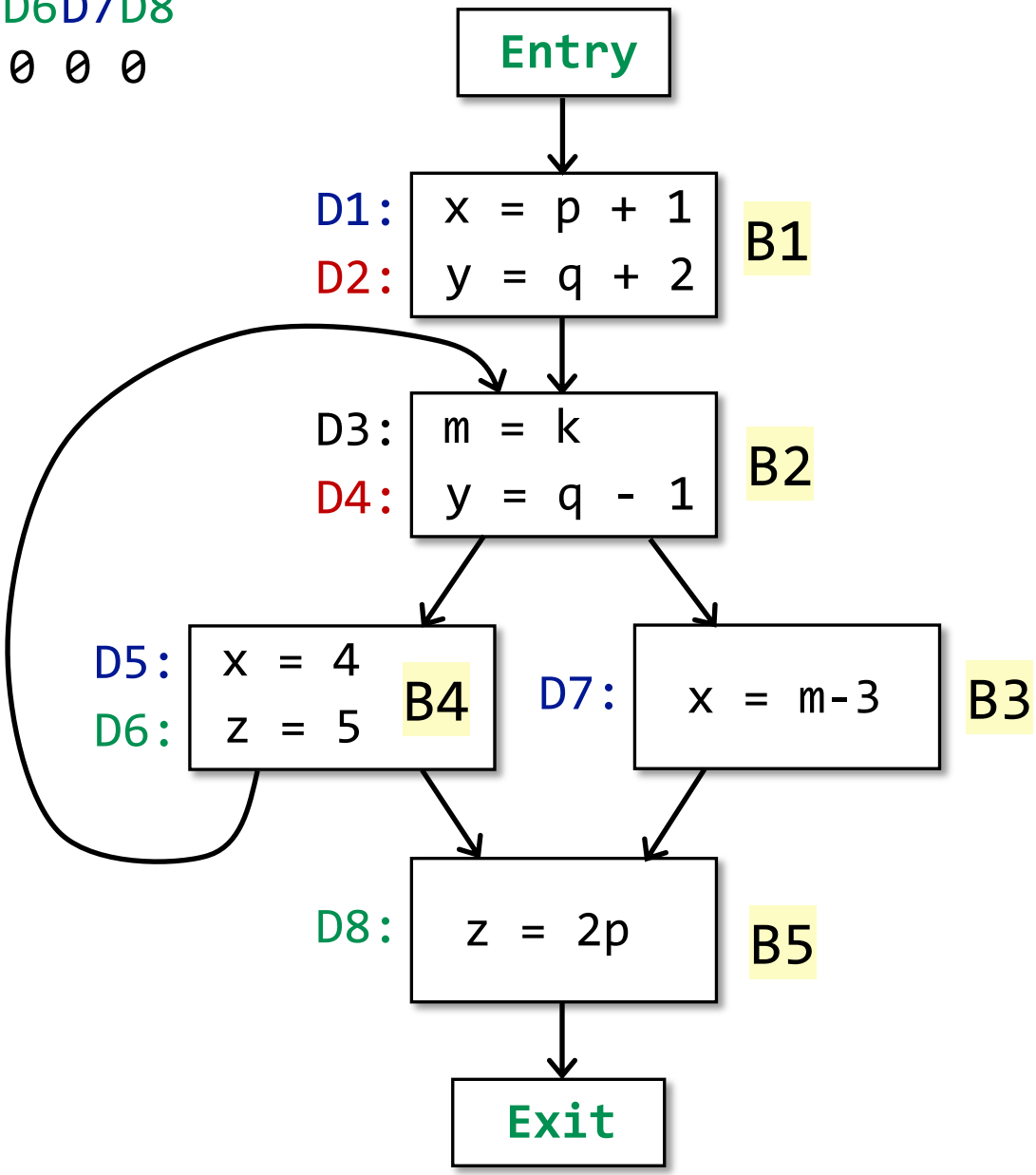

Entry
D1:
x = p + 1
D2:
y = q + 2
B1
D3:
m = k
D4:
y = q - 1
B2
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
D8:
z = 2p
B5
Exit

```
D1
D2
do {
  D3
  D4
  if(…) {
    D5
    D6
  } else {
    D7
    break
  }
} while(…)
D8
```



D1D2D3D4D5D6D7D8

0 0 0 0 0 0 0 0



Algorithm of Reaching Definitions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

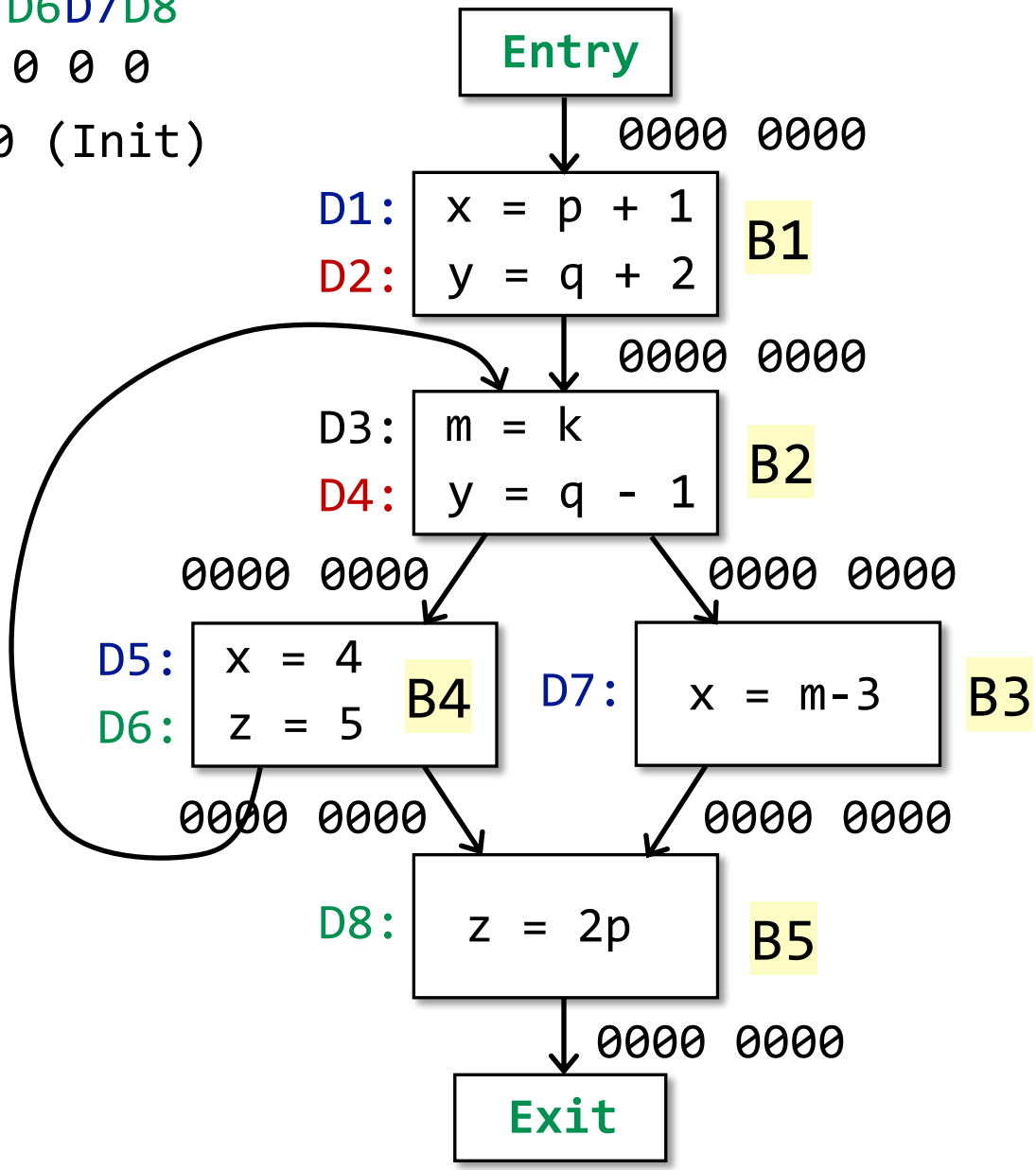
METHOD:

OUT[*entry*] = ∅;
for (each basic block *B**entry*)
    OUT[*B*] = ∅;
while (changes to any OUT occur)
    for (each basic block *B**entry*) {
        IN[*B*] = $\bigcup_{P \text{ a predecessor of } B}$ OUT[*P*];
        OUT[*B*] = gen_B U (IN[*B*] - $kill_B$);
    }

D1D2D3D4D5D6D7D8

0 0 0 0 0 0 0 0

Iteration 0 (Init)



Algorithm of Reaching Definitions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

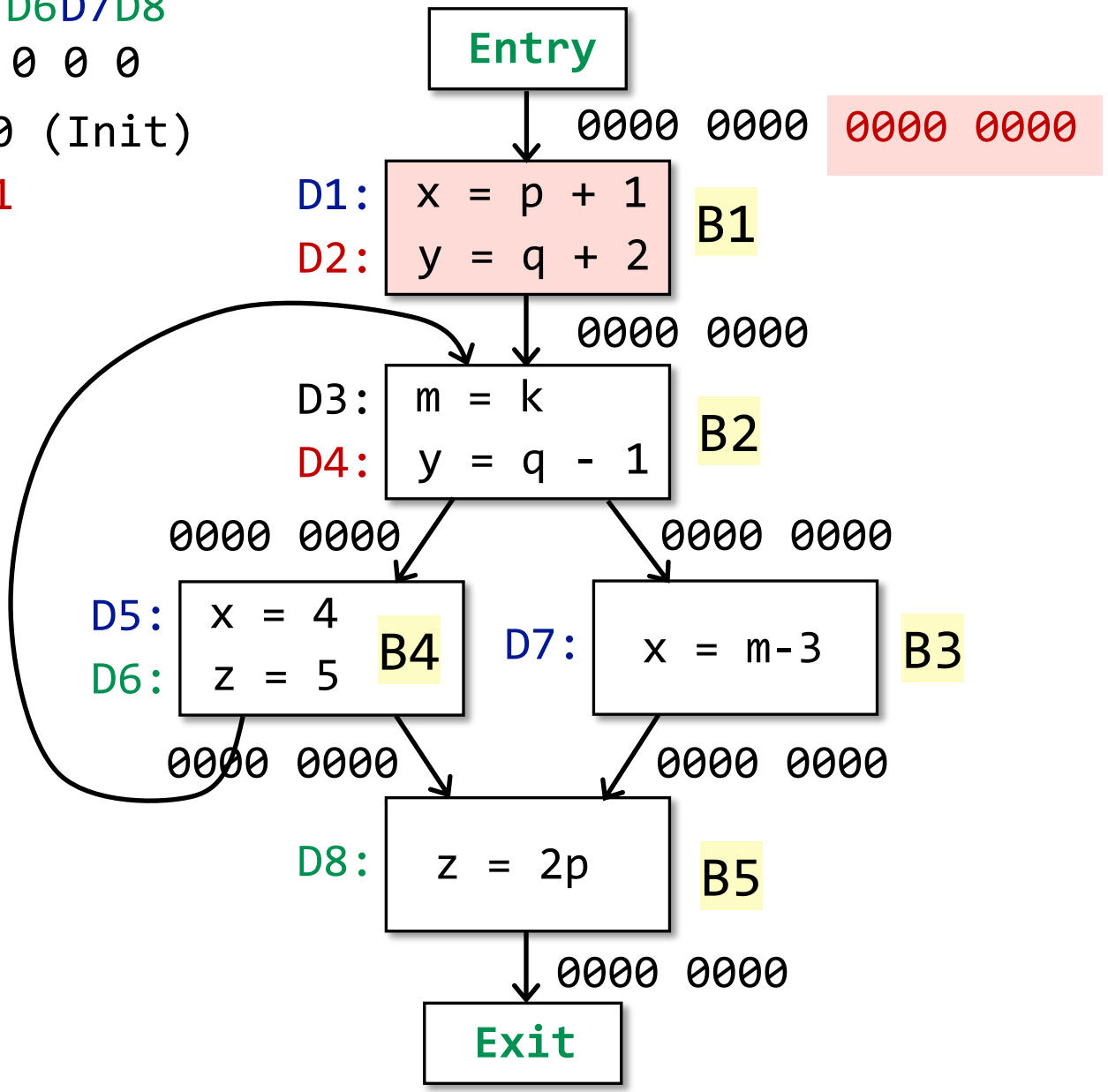
OUT[*entry*] = ∅;
for (each basic block *B**entry*)
    OUT[*B*] = ∅;
while (changes to any OUT occur)
    for (each basic block *B**entry*) {
        IN[*B*] = $\cup_{P \text{ a predecessor of } B}$ OUT[*P*];
        OUT[*B*] = $gen_B \cup (\text{IN}[B] - kill_B)$;
    }

D1D2D3D4D5D6D7D8

0 0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1



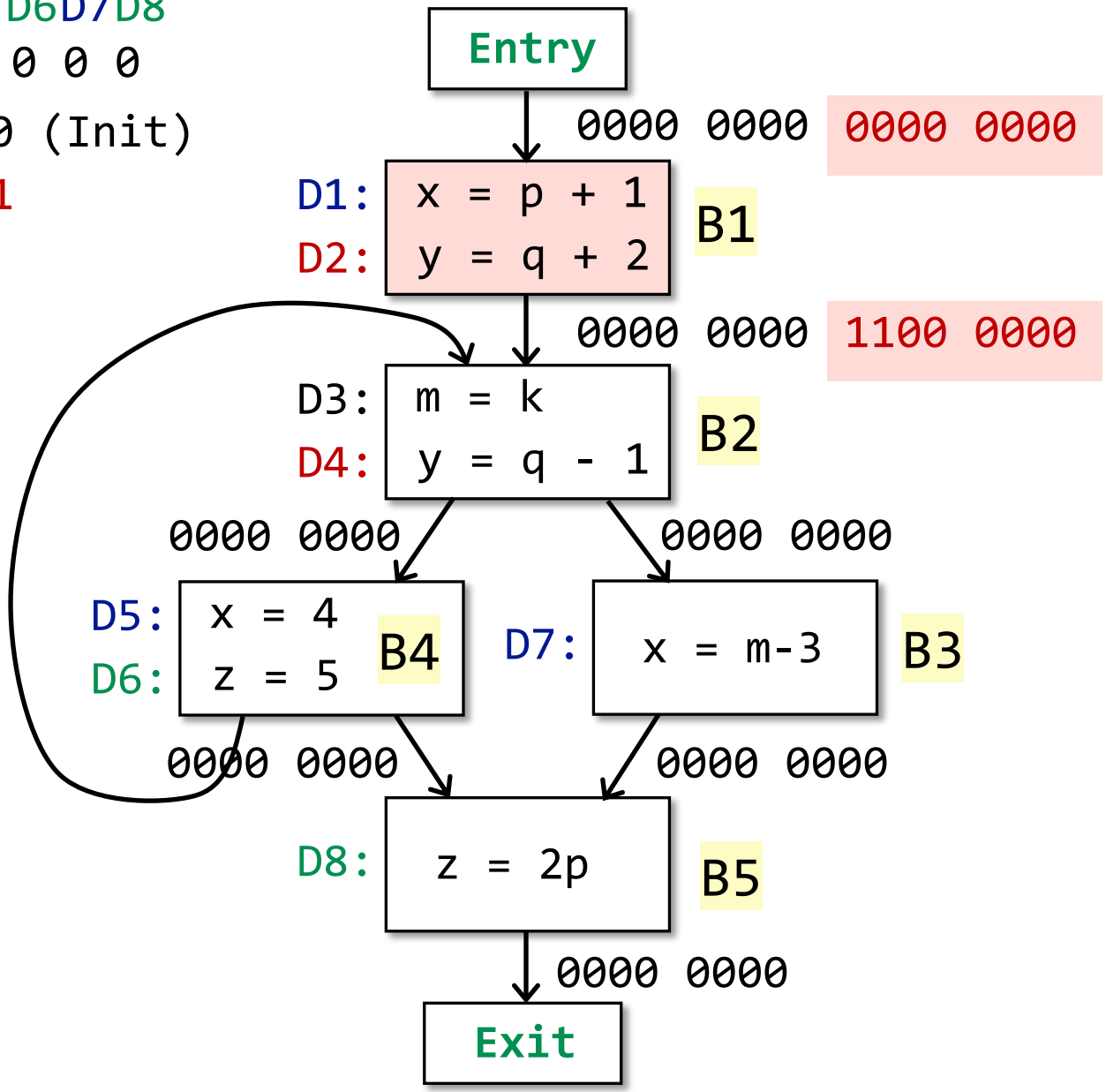
OUT[*B*] = gen_B U (IN[*B*] - $kill_B$);

D1D2D3D4D5D6D7D8

0 0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1

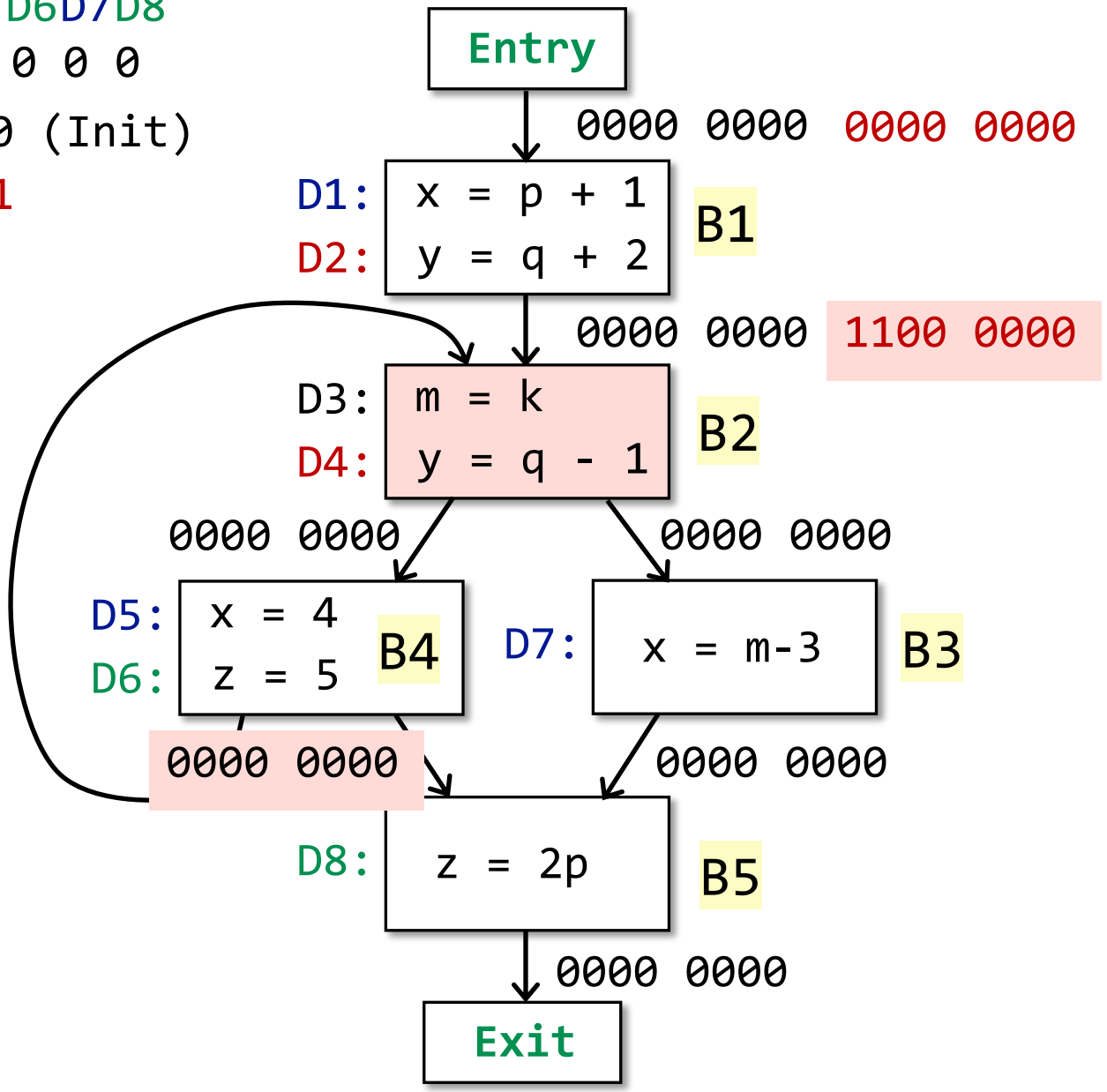


D1D2D3D4D5D6D7D8

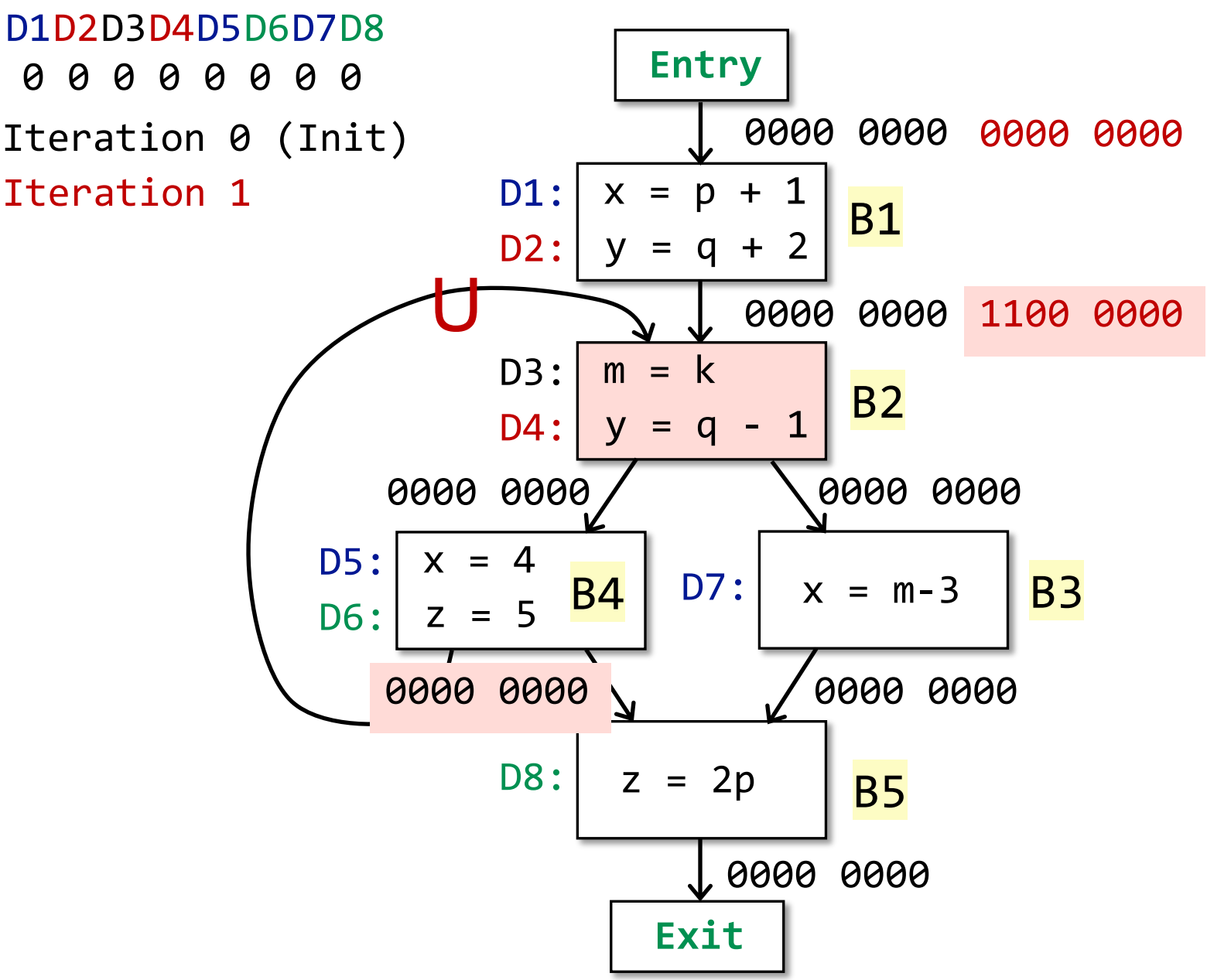
0 0 0 0 0 0 0 0

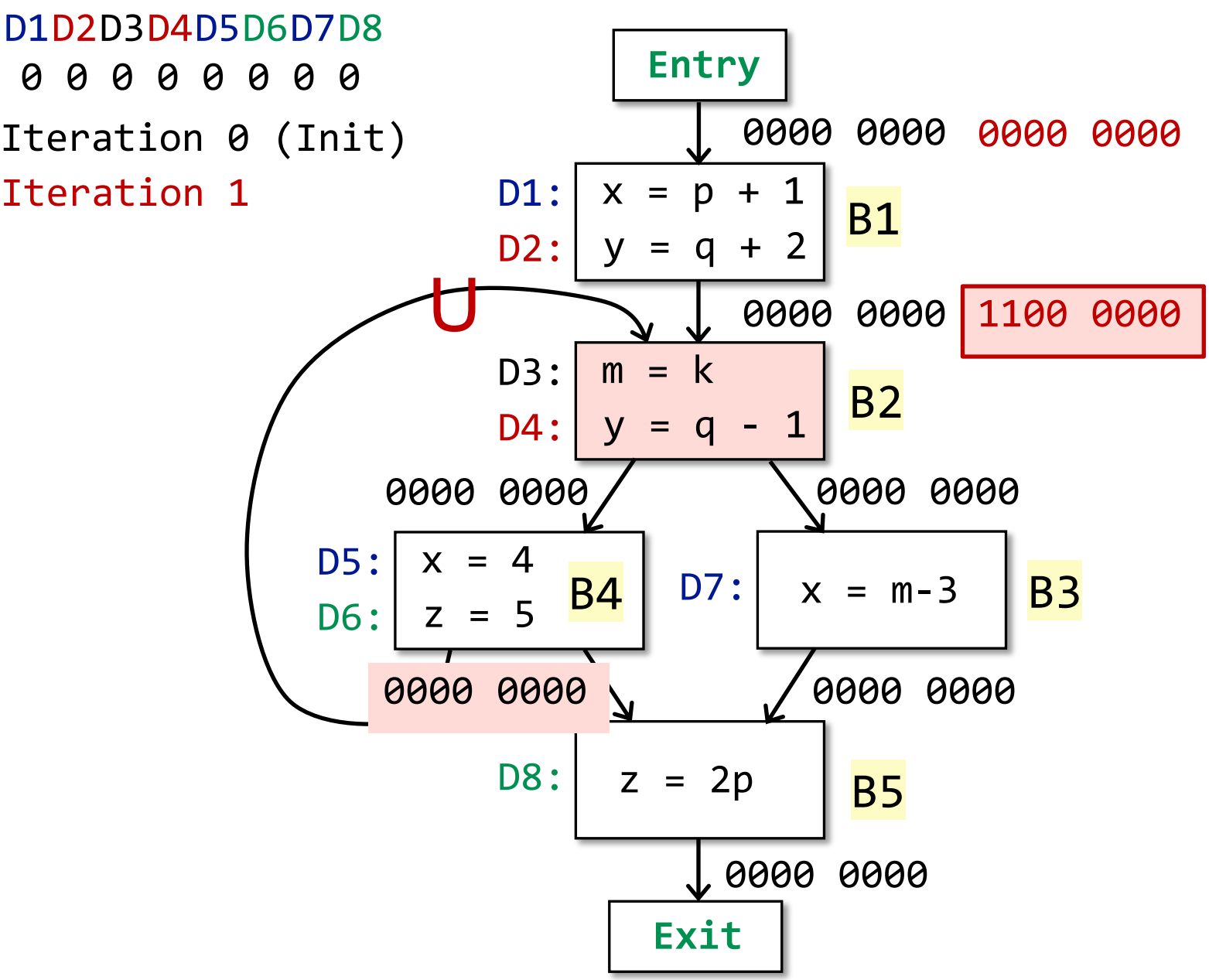
Iteration 0 (Init)

Iteration 1



$IN[B] = \bigcup_{P \text{ a predecessor of } B} OUT[P];$


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
0000 0000 1100 0000
D3:
m = k
D4:
y = q - 1
B2
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0000 0000
0000 0000
D8:
z = 2p
B5
0000 0000
Exit

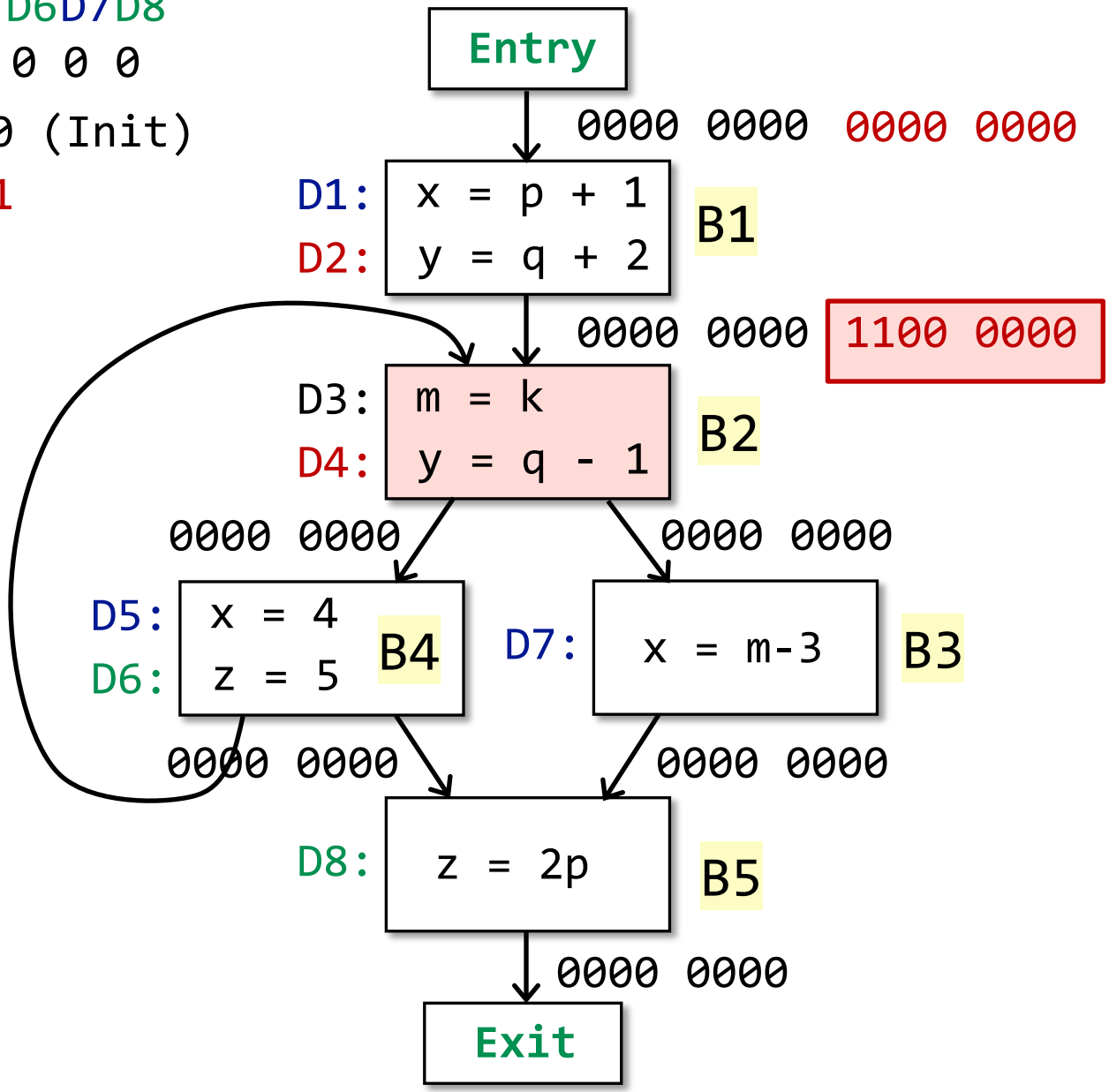

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
0000 0000
1100 0000
U
D3:
m = k
D4:
y = q - 1
B2
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0000 0000
0000 0000
D8:
z = 2p
B5
0000 0000
Exit

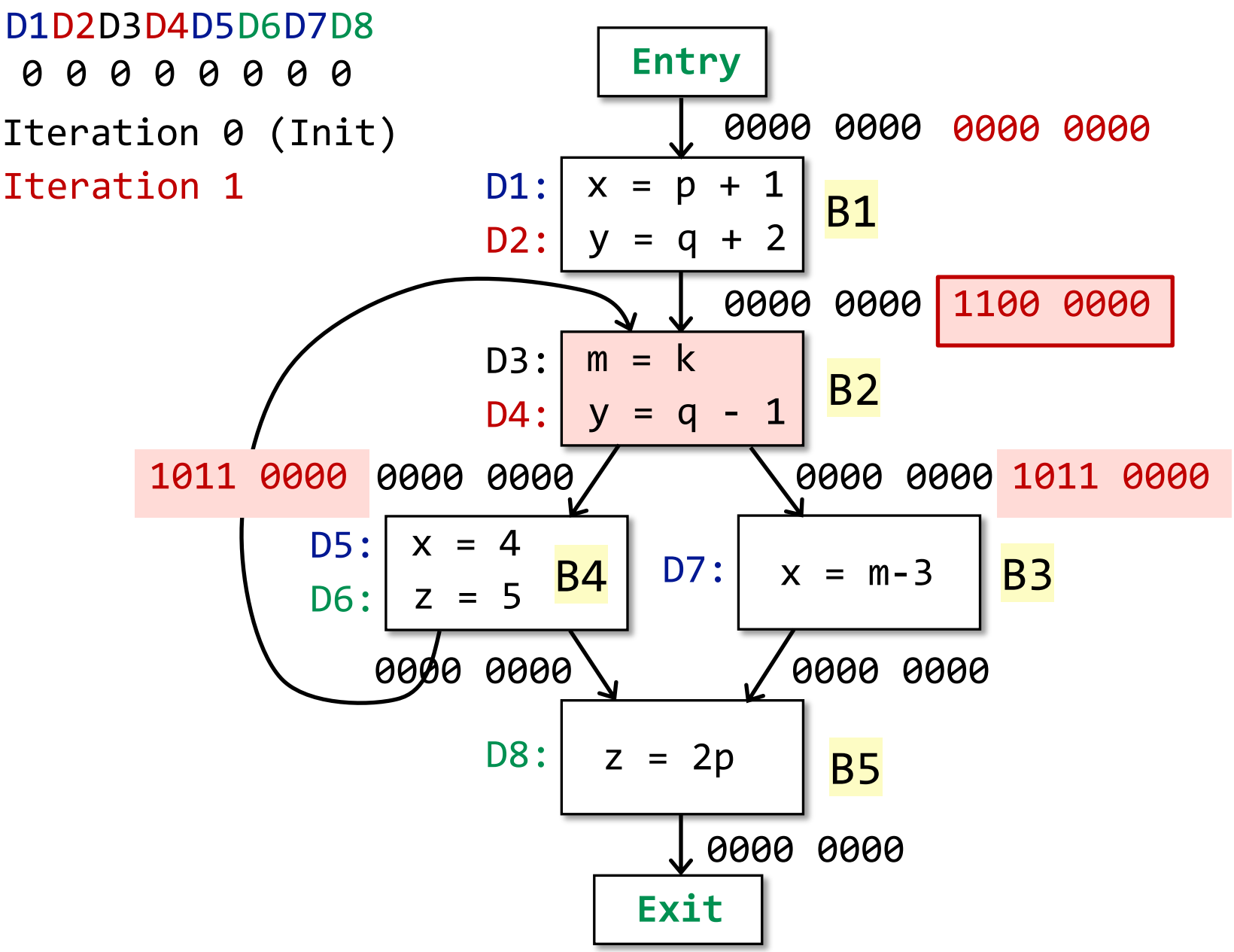
D1D2D3D4D5D6D7D8

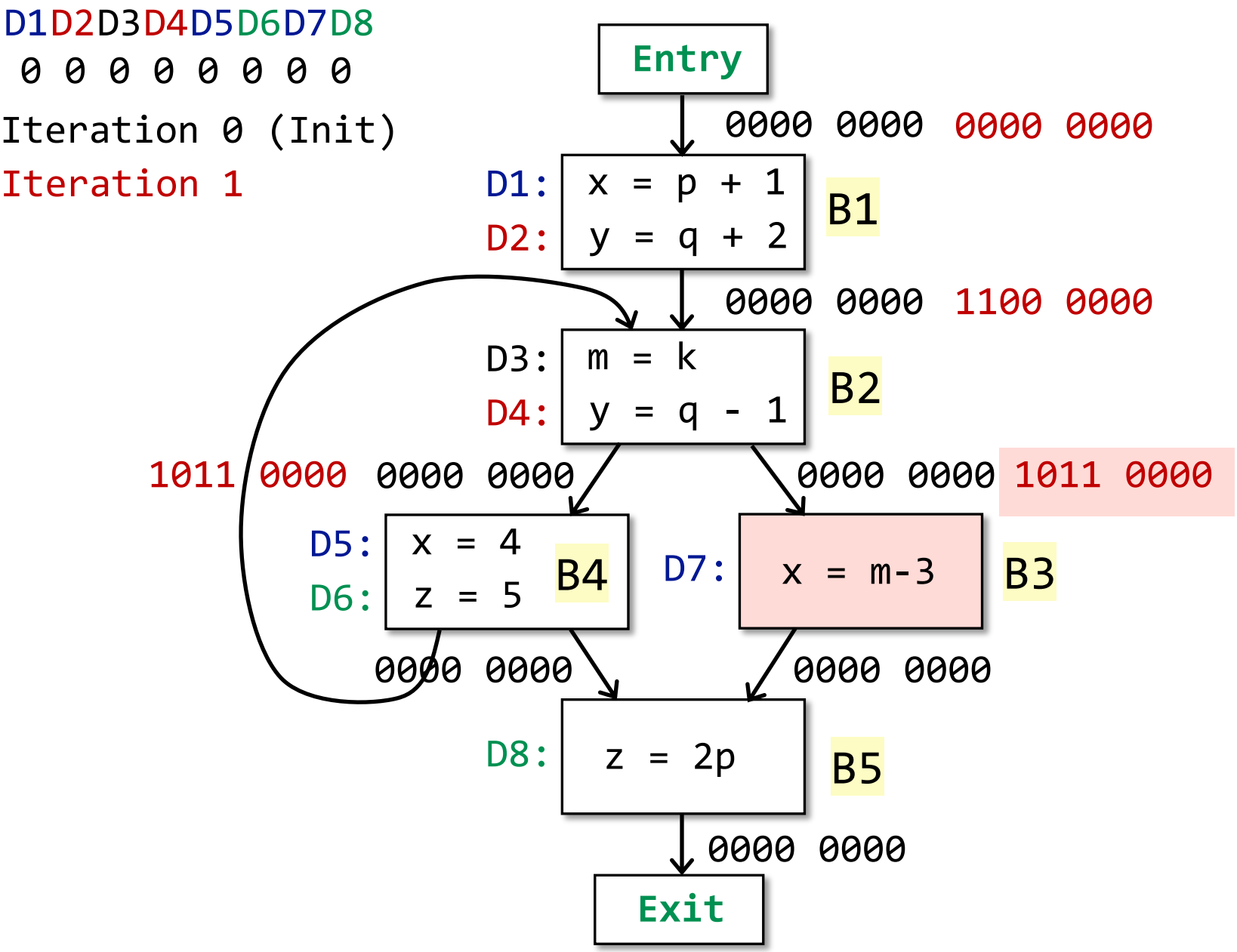
0 0 0 0 0 0 0 0

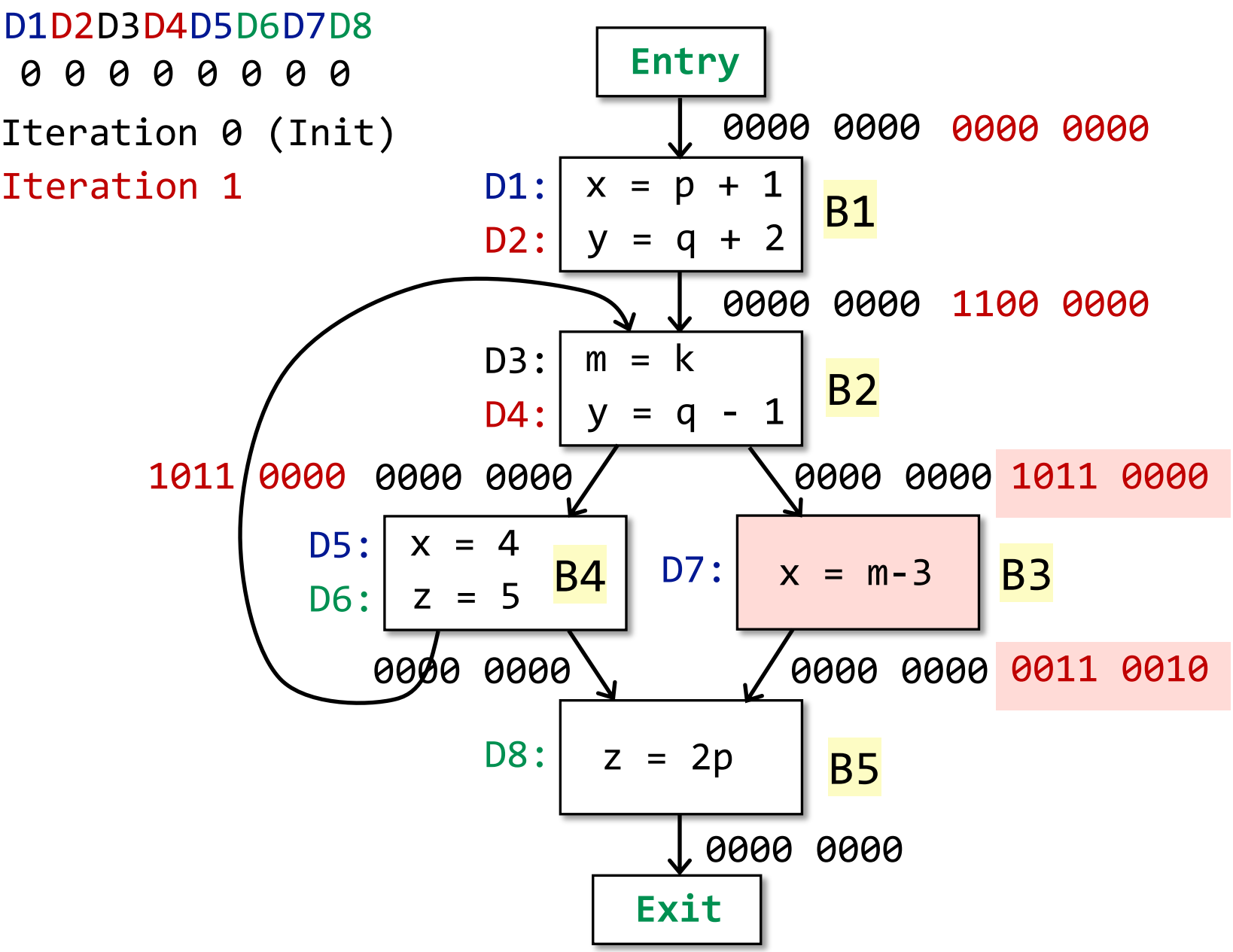
Iteration 0 (Init)

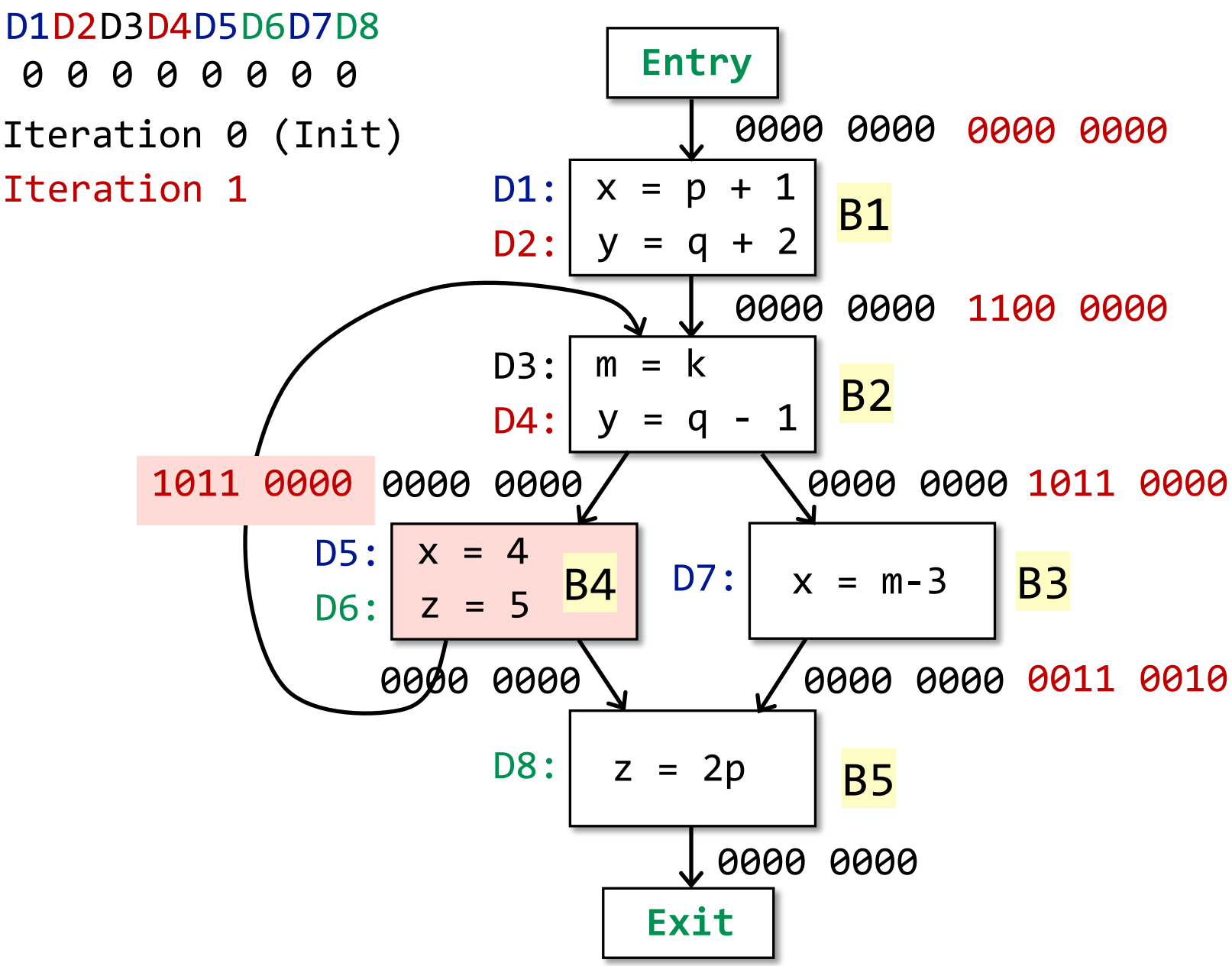
Iteration 1

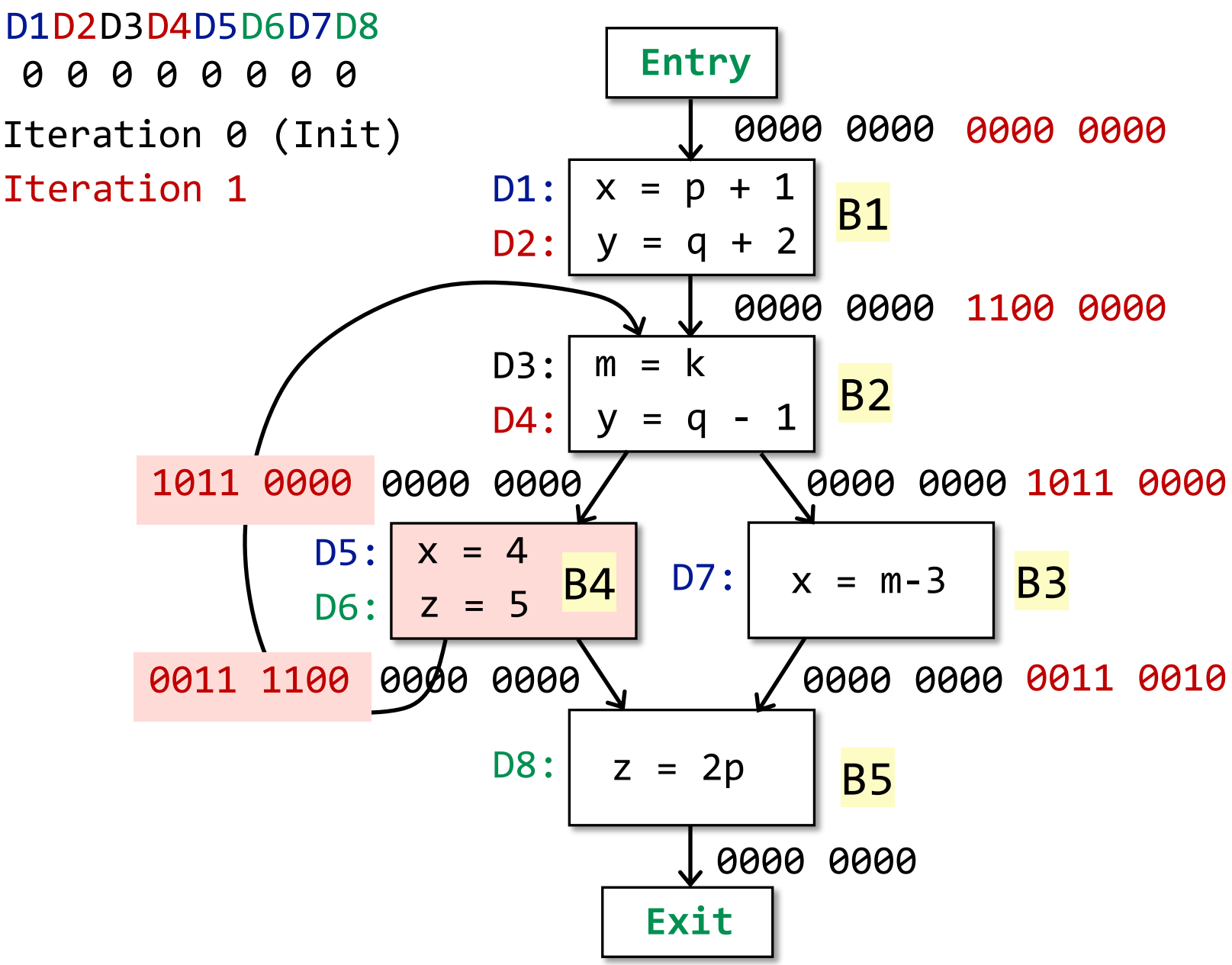


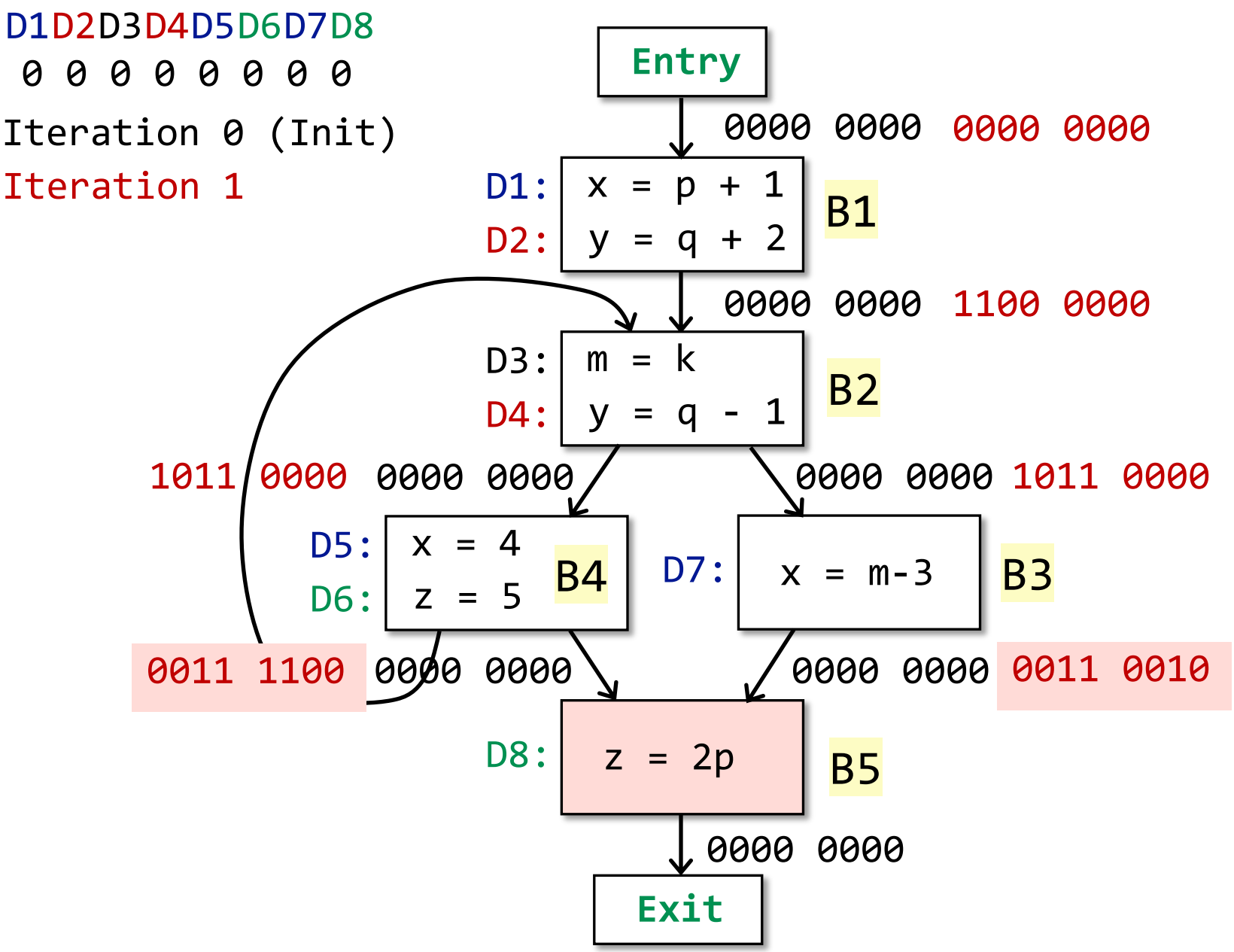

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1: x = p + 1
D2: y = q + 2
B1
0000 0000
1100 0000
D3: m = k
D4: y = q - 1
B2
1011 0000
0000 0000
0000 0000
1011 0000
D5: x = 4
D6: z = 5
B4
D7: x = m-3
B3
0000 0000
0000 0000
D8: z = 2p
B5
0000 0000
Exit

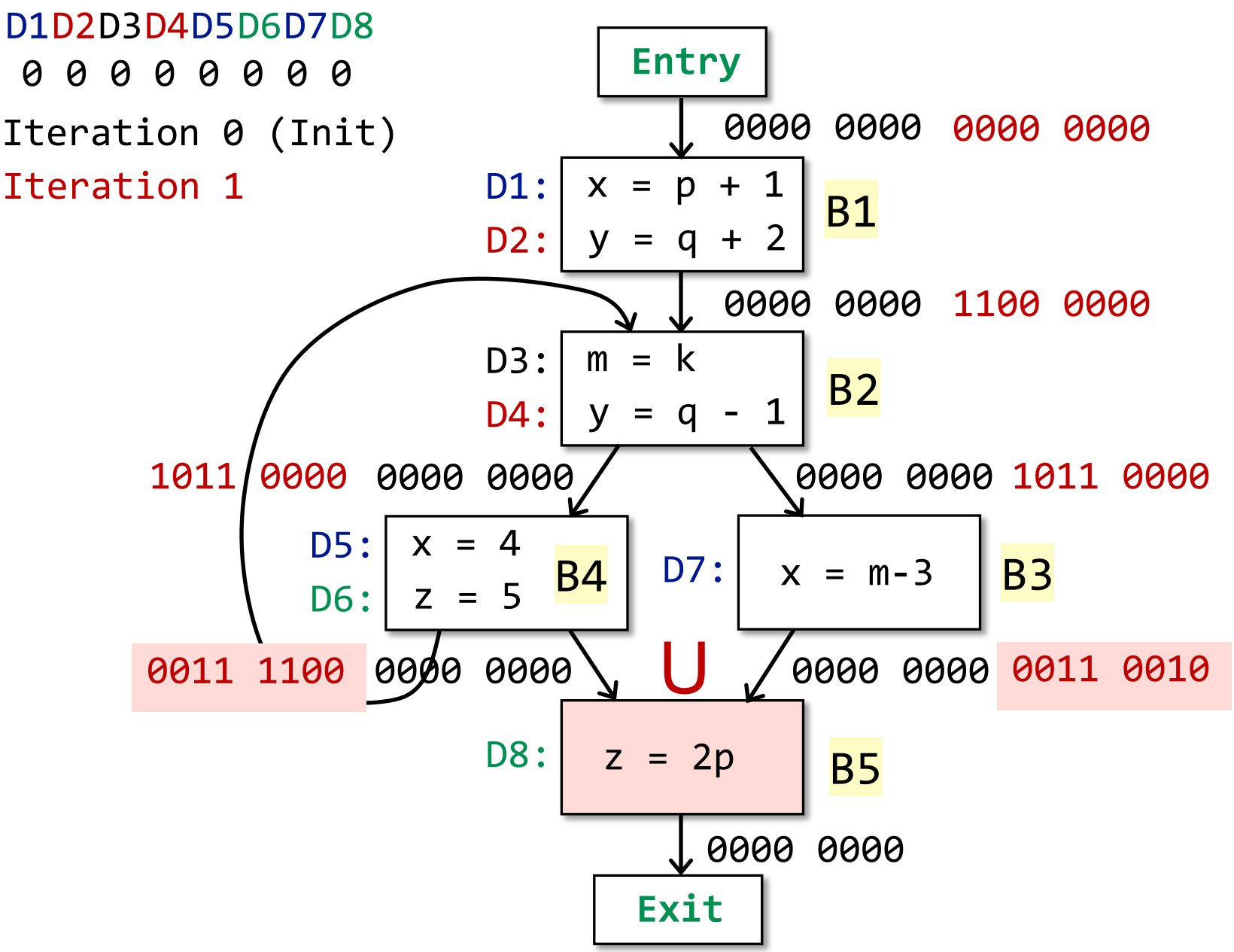

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1: x = p + 1
D2: y = q + 2
B1
0000 0000 1100 0000
D3: m = k
D4: y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5: x = 4
D6: z = 5
B4
D7: x = m-3
B3
0000 0000
0000 0000
D8: z = 2p
B5
0000 0000
Exit

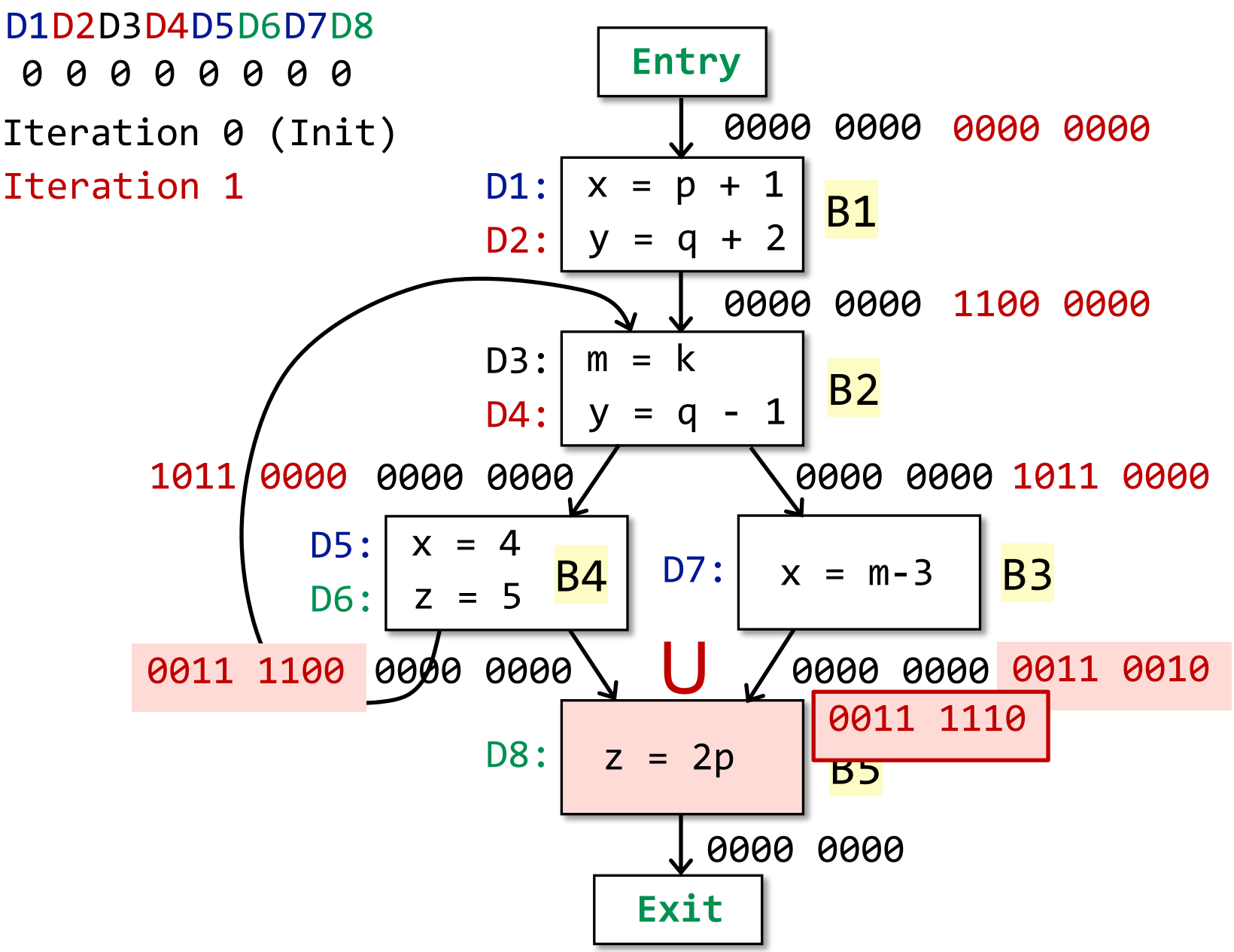

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1: x = p + 1
D2: y = q + 2
B1
0000 0000 1100 0000
D3: m = k
D4: y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5: x = 4
D6: z = 5
B4
D7: x = m-3
B3
0000 0000
0000 0000 0011 0010
D8: z = 2p
B5
0000 0000
Exit

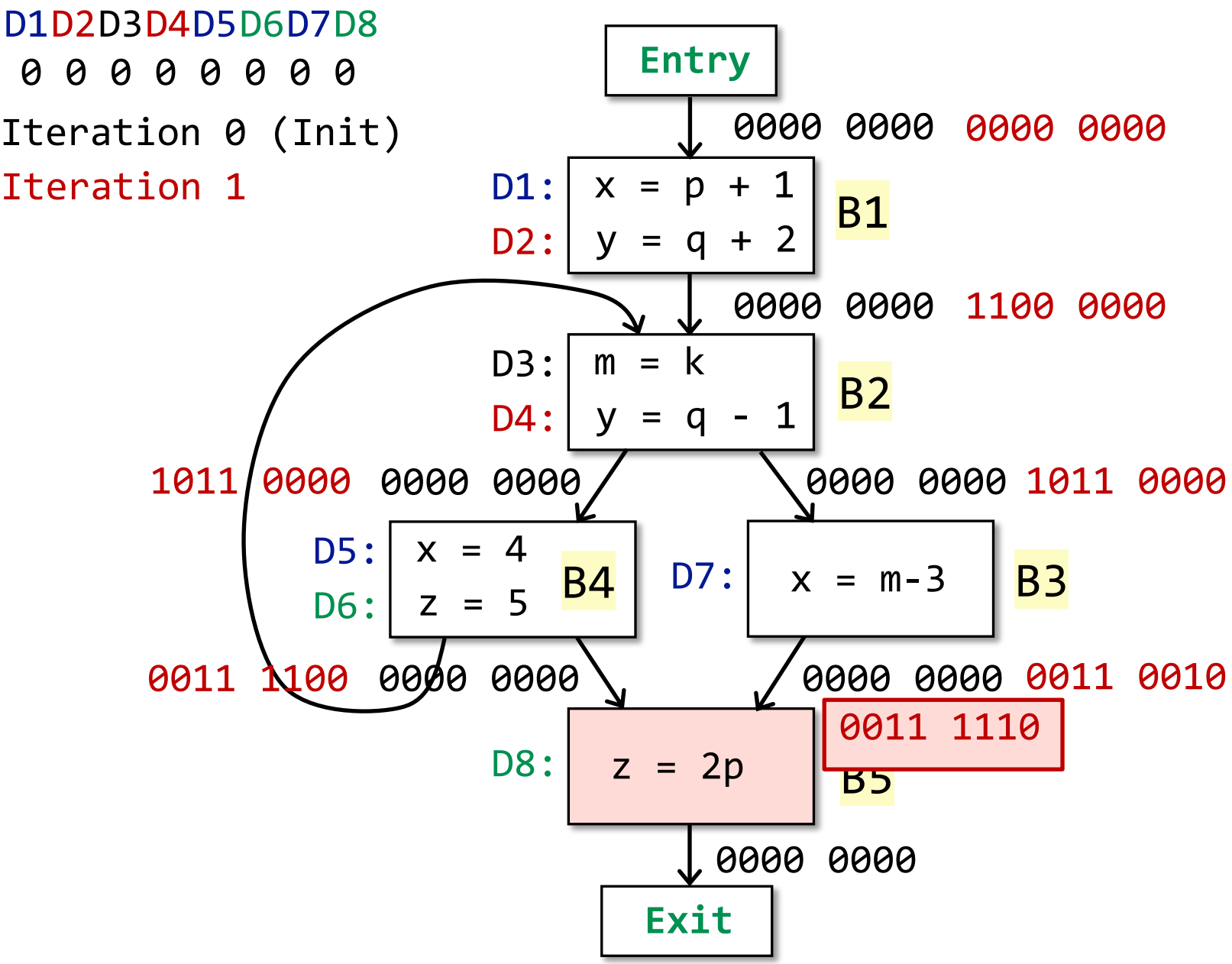

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
0000 0000 1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 0000
0000 0000
0000 0000 1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0000 0000
0000 0000 0011 0010
D8:
z = 2p
B5
0000 0000
Exit

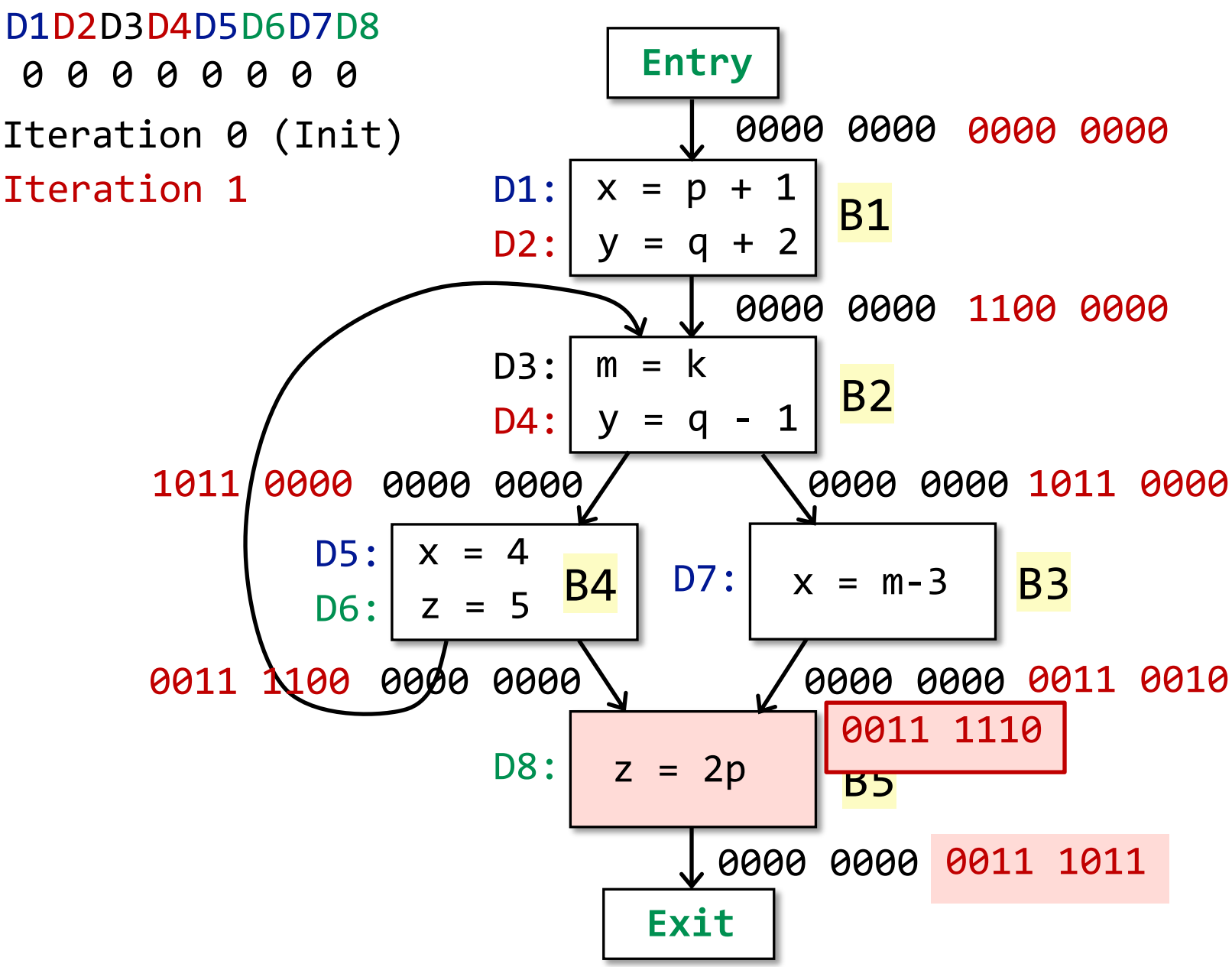

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
0000 0000 1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 0000
0000 0000
0000 0000 1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
0000 0000 0011 0010
D8:
z = 2p
B5
0000 0000
Exit

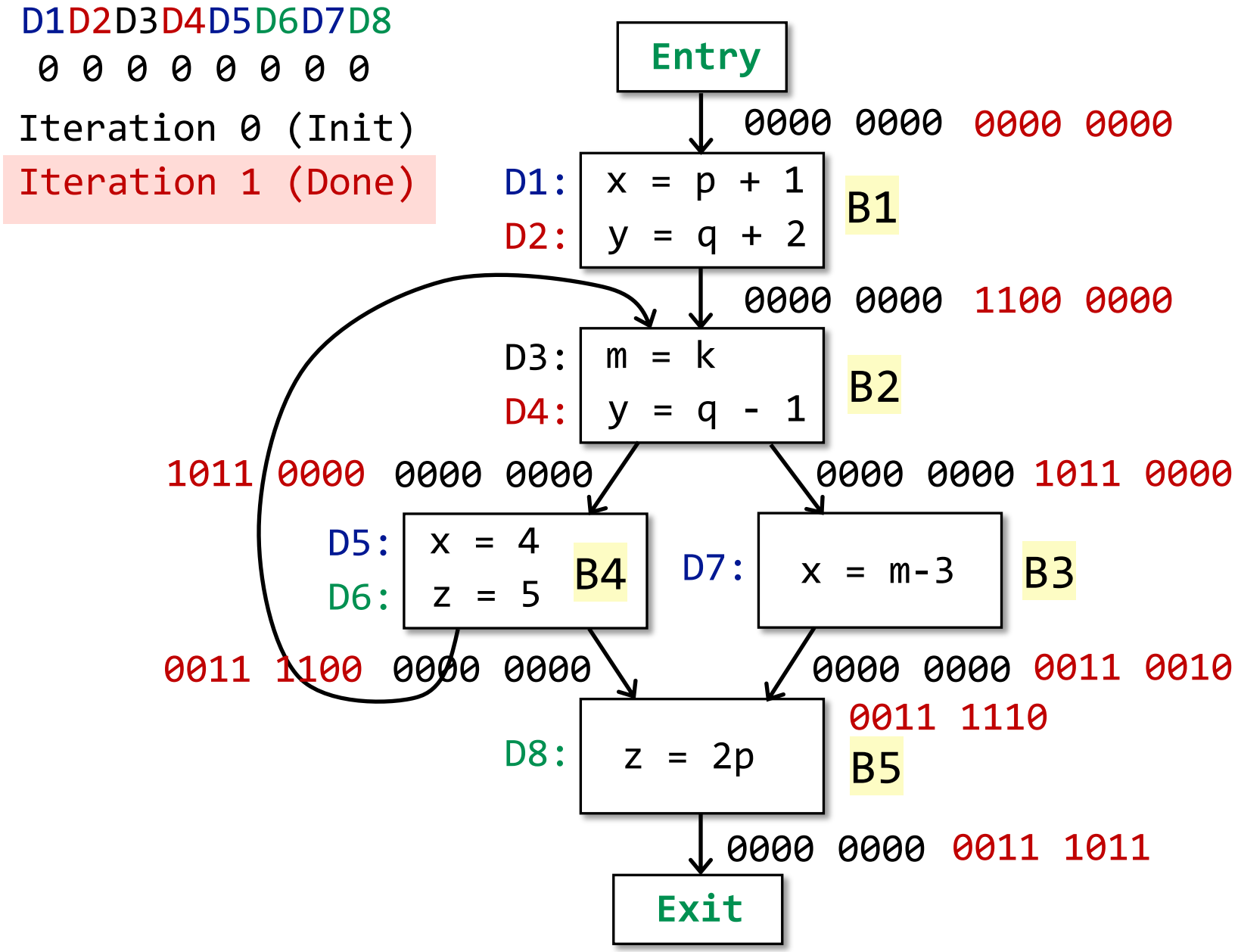

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1:
D2:
x = p + 1
y = q + 2
B1
0000 0000 1100 0000
D3:
D4:
m = k
y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5:
D6:
x = 4
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
0000 0000
0011 0010
D8:
z = 2p
B5
0000 0000
Exit


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1:
D2:
x = p + 1
y = q + 2
B1
0000 0000 1100 0000
D3:
D4:
m = k
y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5:
D6:
x = 4
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
U
0000 0000
0011 0010
D8:
z = 2p
B5
0000 0000
Exit


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1:
D2:
x = p + 1
y = q + 2
B1
0000 0000 1100 0000
D3:
D4:
m = k
y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5:
D6:
x = 4
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
U
0000 0000 0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
Exit


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1: x = p + 1
D2: y = q + 2
B1
0000 0000 1100 0000
D3: m = k
D4: y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5: x = 4
D6: z = 5
B4
D7: x = m-3
B3
0011 1100 0000 0000
0000 0000 0011 0010
D8: z = 2p
0011 1110
B5
0000 0000
Exit


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1
Entry
0000 0000 0000 0000
D1:
D2:
x = p + 1
y = q + 2
B1
0000 0000 1100 0000
D3:
D4:
m = k
y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5:
D6:
x = 4
z = 5
B4
D7:
x = m-3
B3
0011 1100 0000 0000
0000 0000 0011 0010
D8:
z = 2p
0011 1110
B5
0000 0000 0011 1011
Exit


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Entry
0000 0000 0000 0000
D1:
D2:
x = p + 1
y = q + 2
B1
0000 0000 1100 0000
D3:
D4:
m = k
y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5:
D6:
x = 4
z = 5
B4
D7:
x = m-3
B3
0011 1100 0000 0000
0000 0000 0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000 0011 1011
Exit

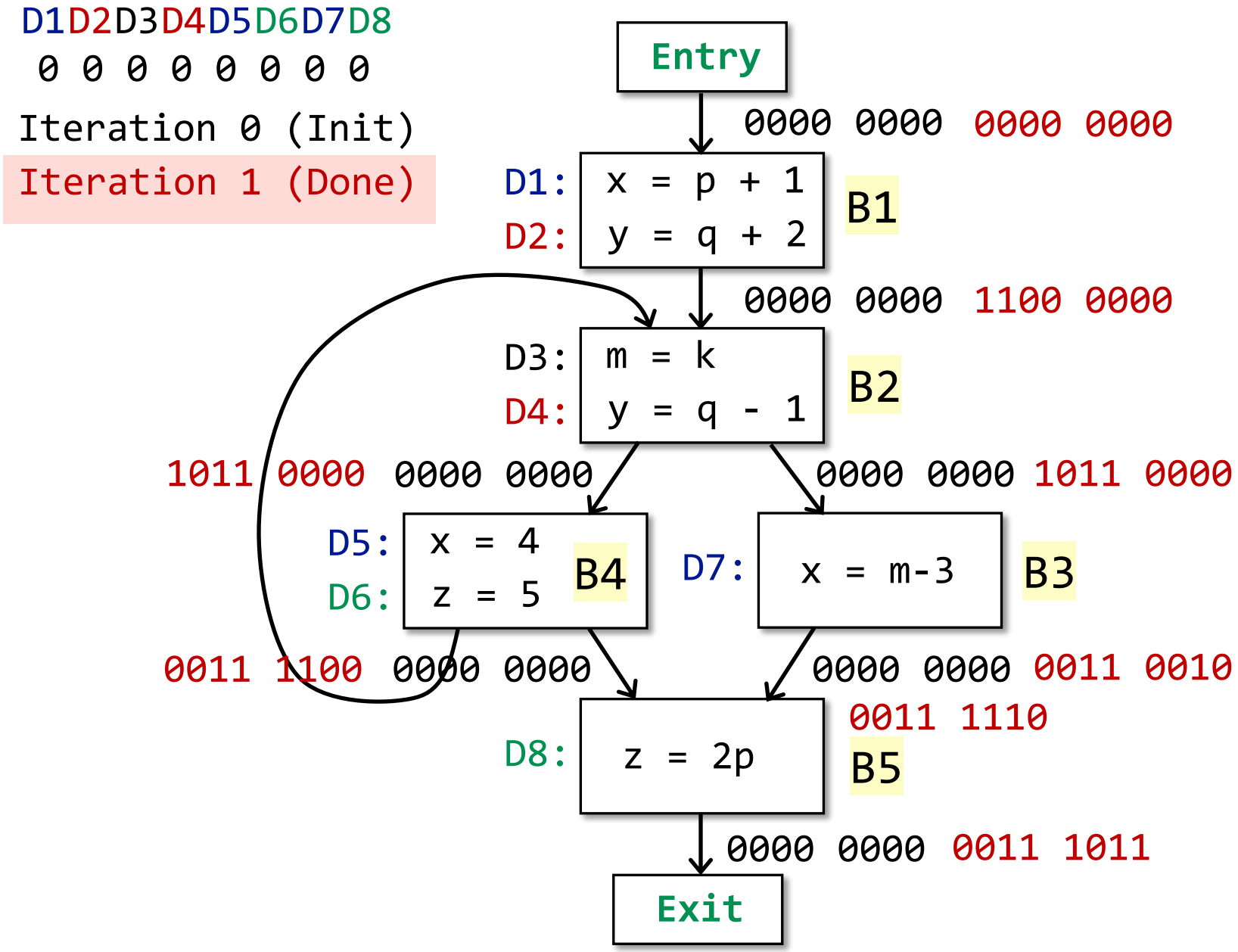
Algorithm of Reaching Definitions Analysis

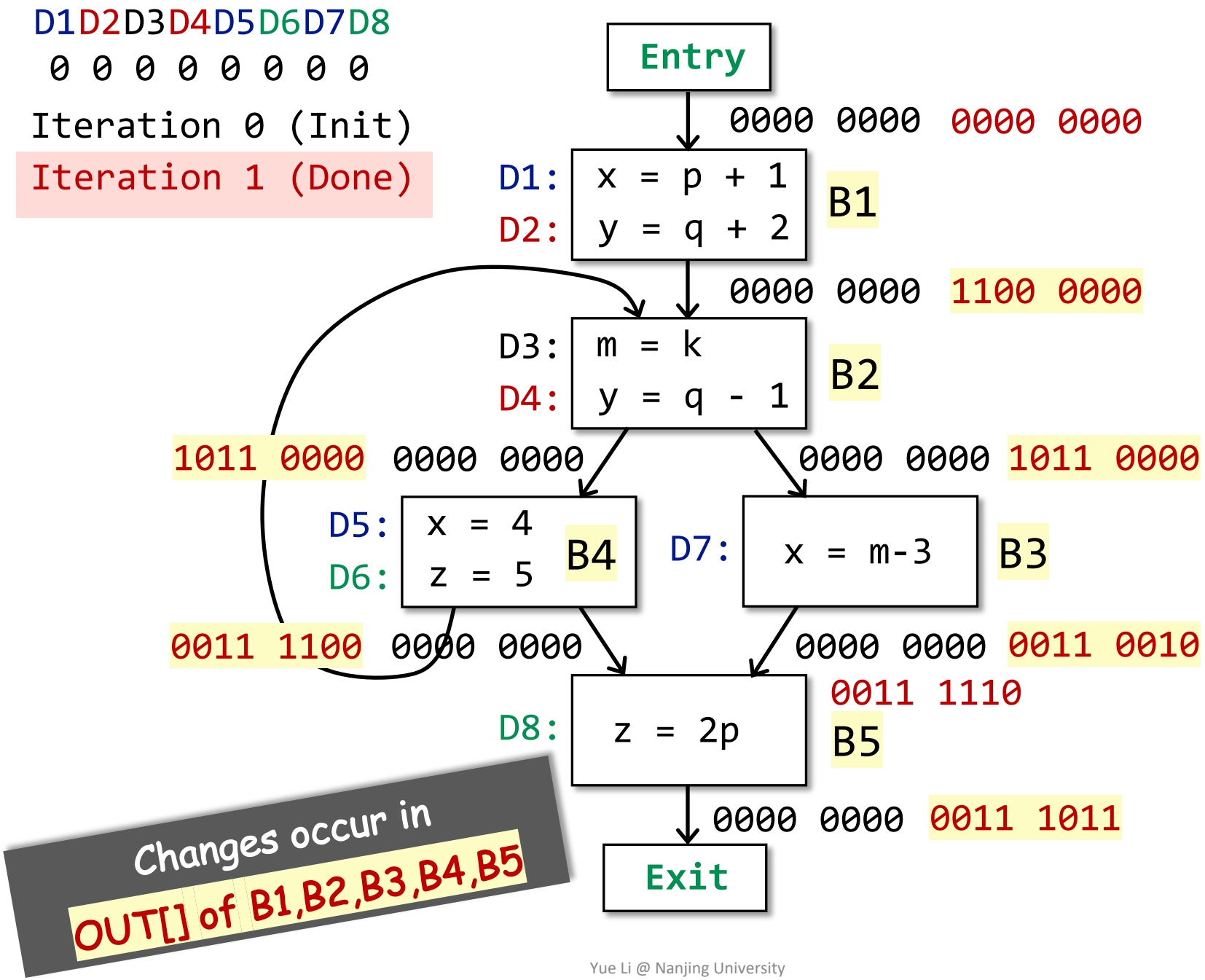
INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

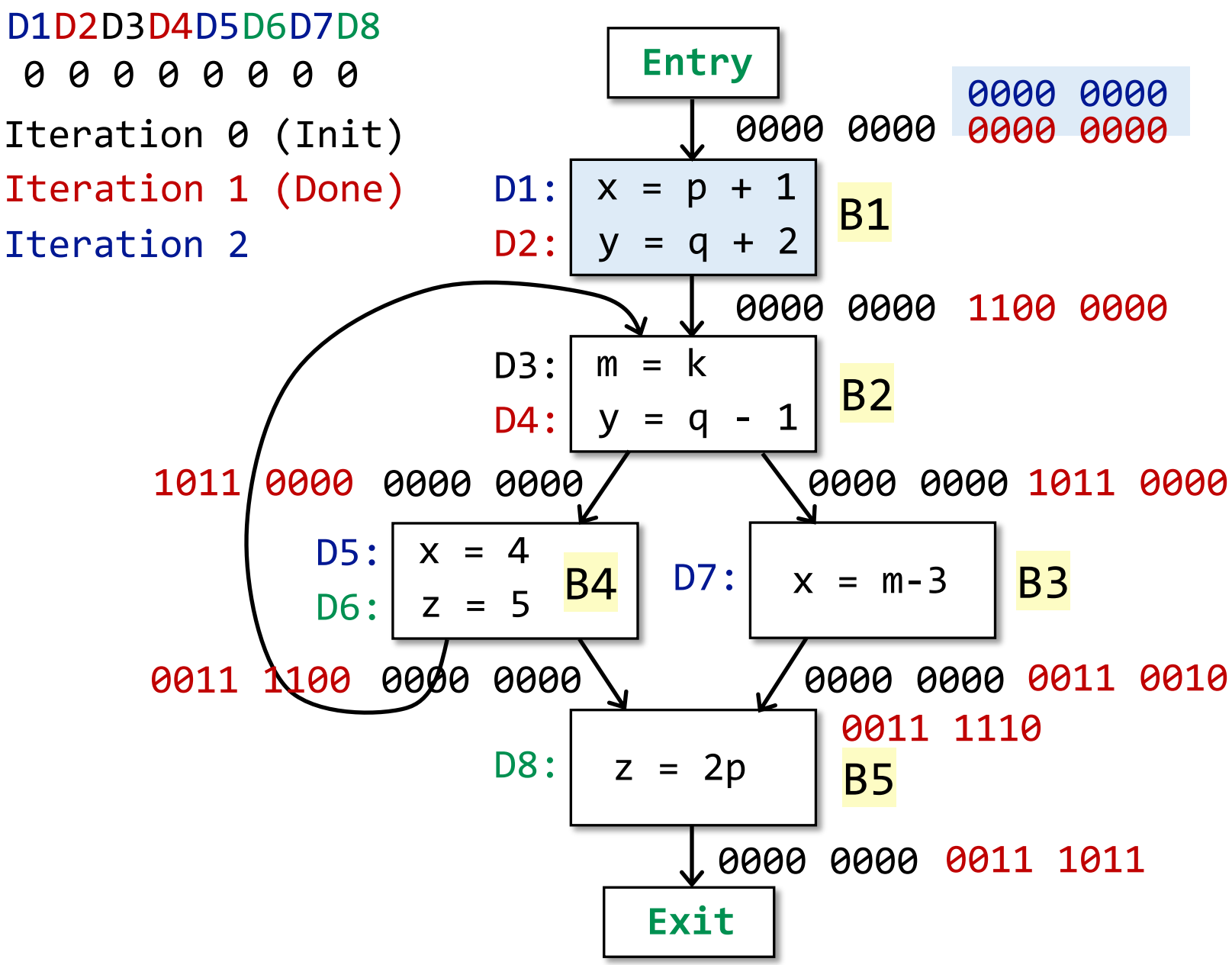
OUTPUT: IN[B] and OUT[B] for each basic block B

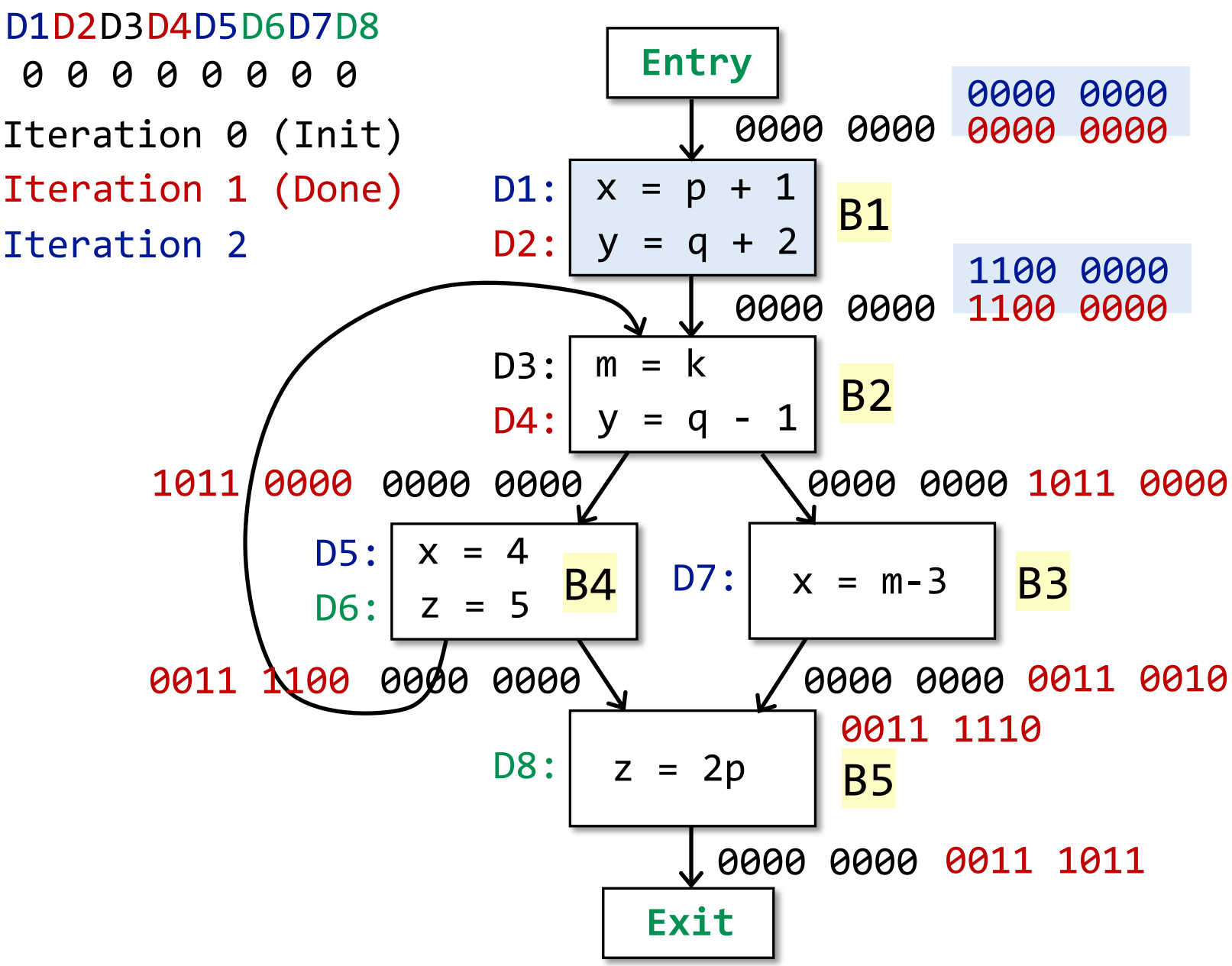
METHOD:

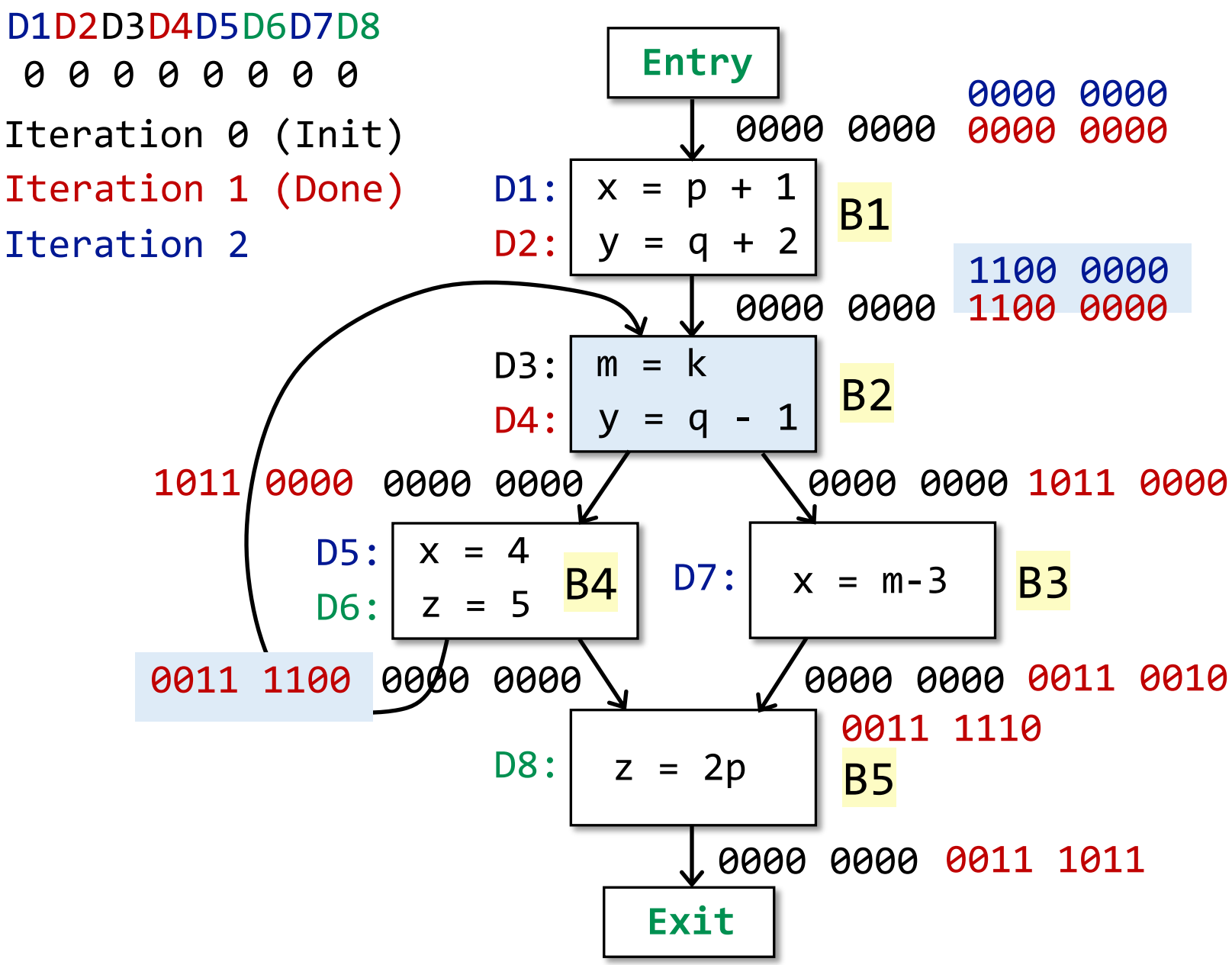
OUT[*entry*] = ∅;
for (each basic block *B**entry*)
    OUT[*B*] = ∅;
while (changes to any OUT occur)
    for (each basic block *B**entry*) {
        IN[*B*] = $\bigcup_{P \text{ a predecessor of } B}$ OUT[*P*];
        OUT[*B*] = gen_B U (IN[*B*] - $kill_B$);
    }

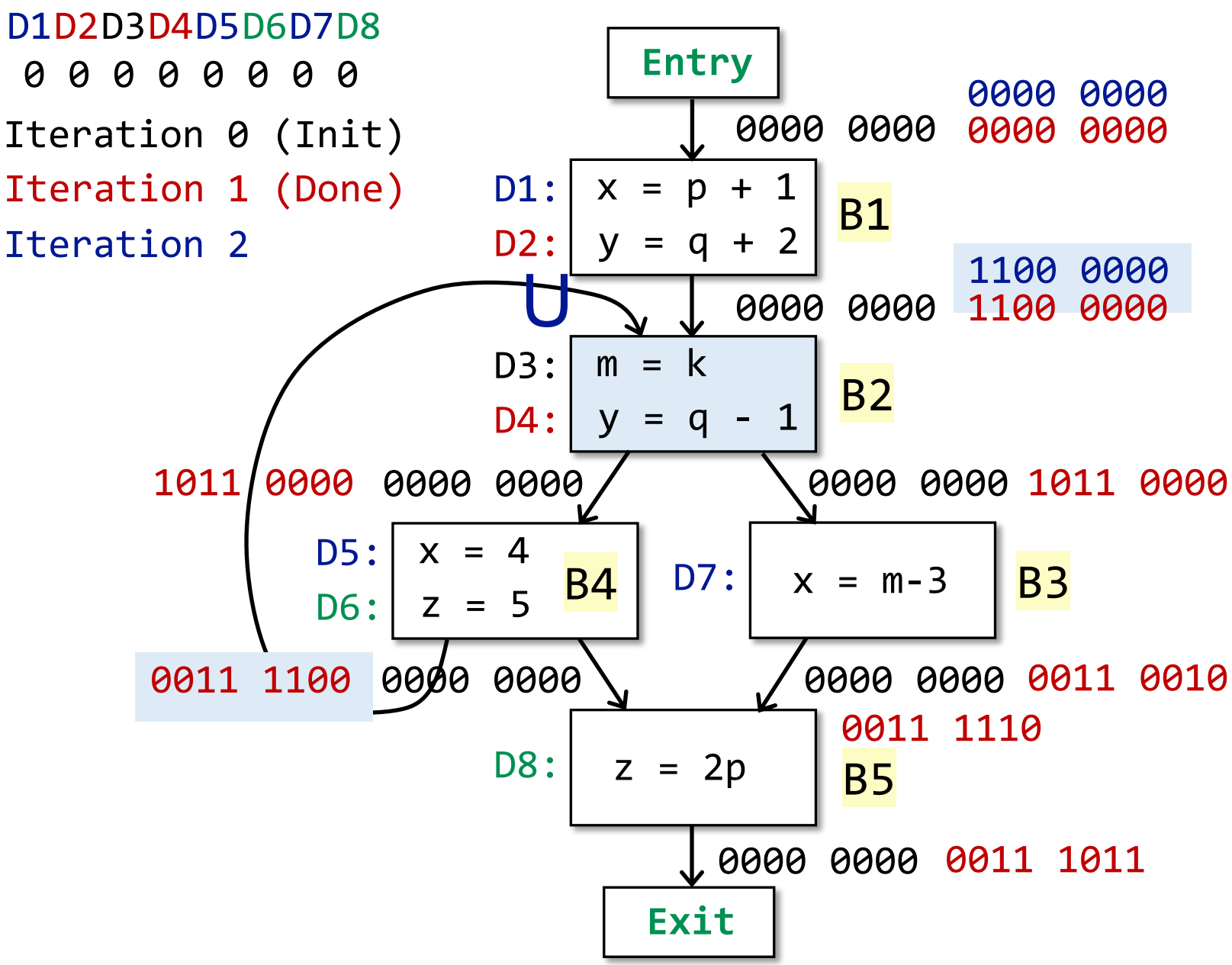

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Entry
0000 0000 0000 0000
D1:
D2:
x = p + 1
y = q + 2
B1
0000 0000 1100 0000
D3:
D4:
m = k
y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5:
D6:
x = 4
z = 5
B4
D7:
x = m-3
B3
0011 1100 0000 0000
0000 0000 0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000 0011 1011
Exit

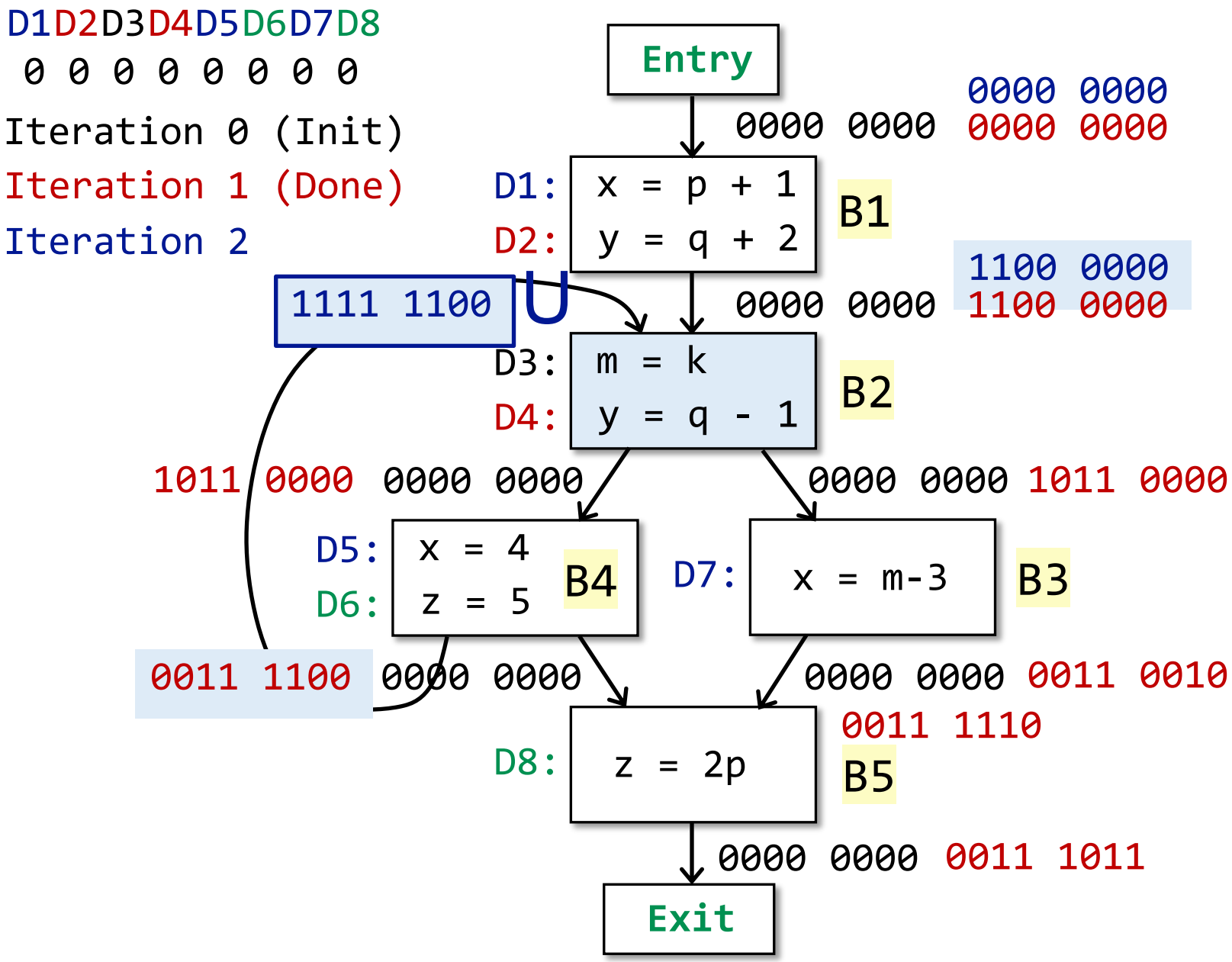

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Entry
0000 0000 0000 0000
D1: x = p + 1
D2: y = q + 2
B1
0000 0000 1100 0000
D3: m = k
D4: y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5: x = 4
D6: z = 5
B4
D7: x = m-3
B3
0011 1100 0000 0000
0000 0000 0011 0010
0011 1110
D8: z = 2p
B5
0000 0000 0011 1011
Exit
Changes occur in
OUT[] of B1,B2,B3,B4,B5

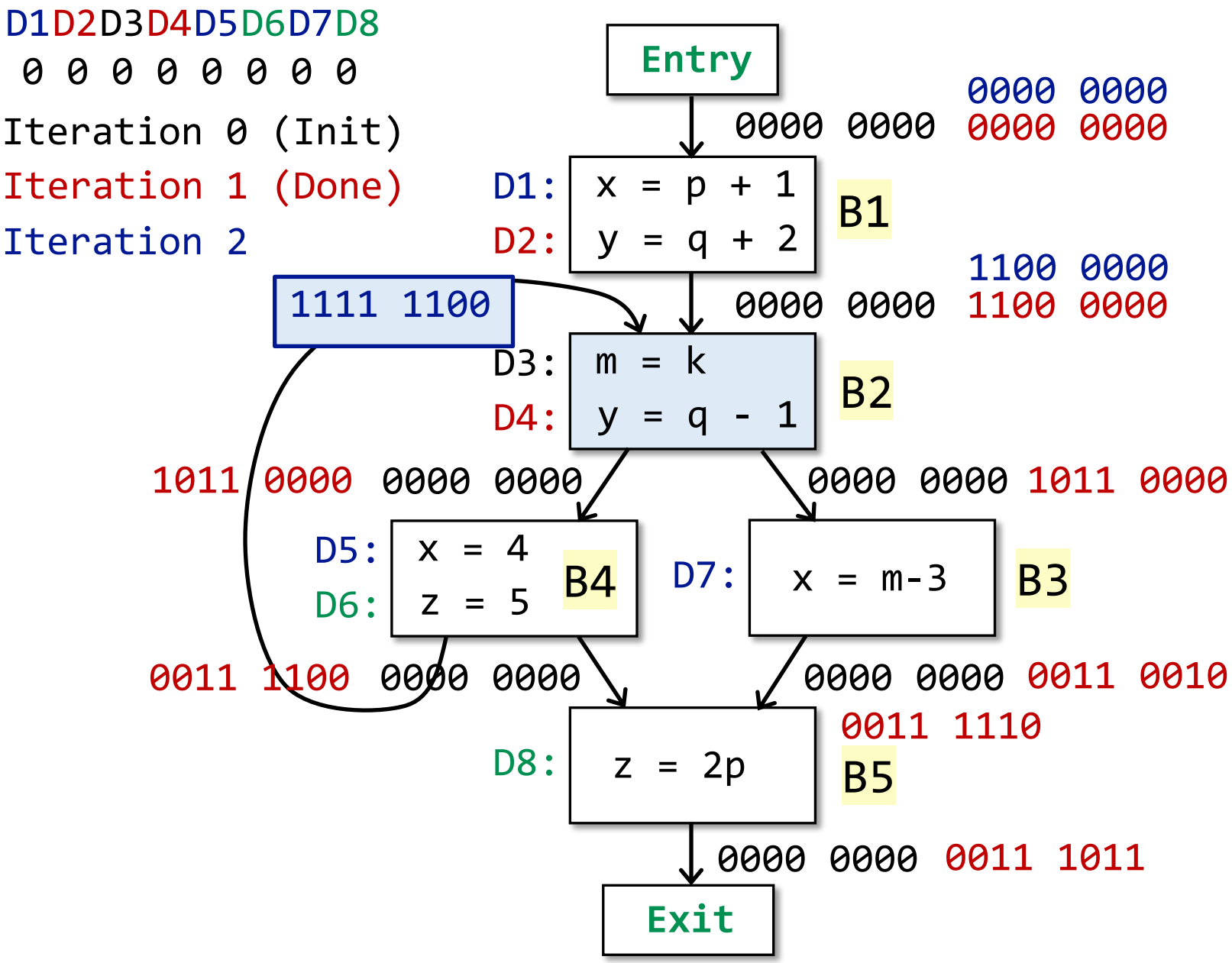

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
0000 0000 1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 0000 0000 0000
0000 0000 1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100 0000 0000
0000 0000 0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000 0011 1011
Exit

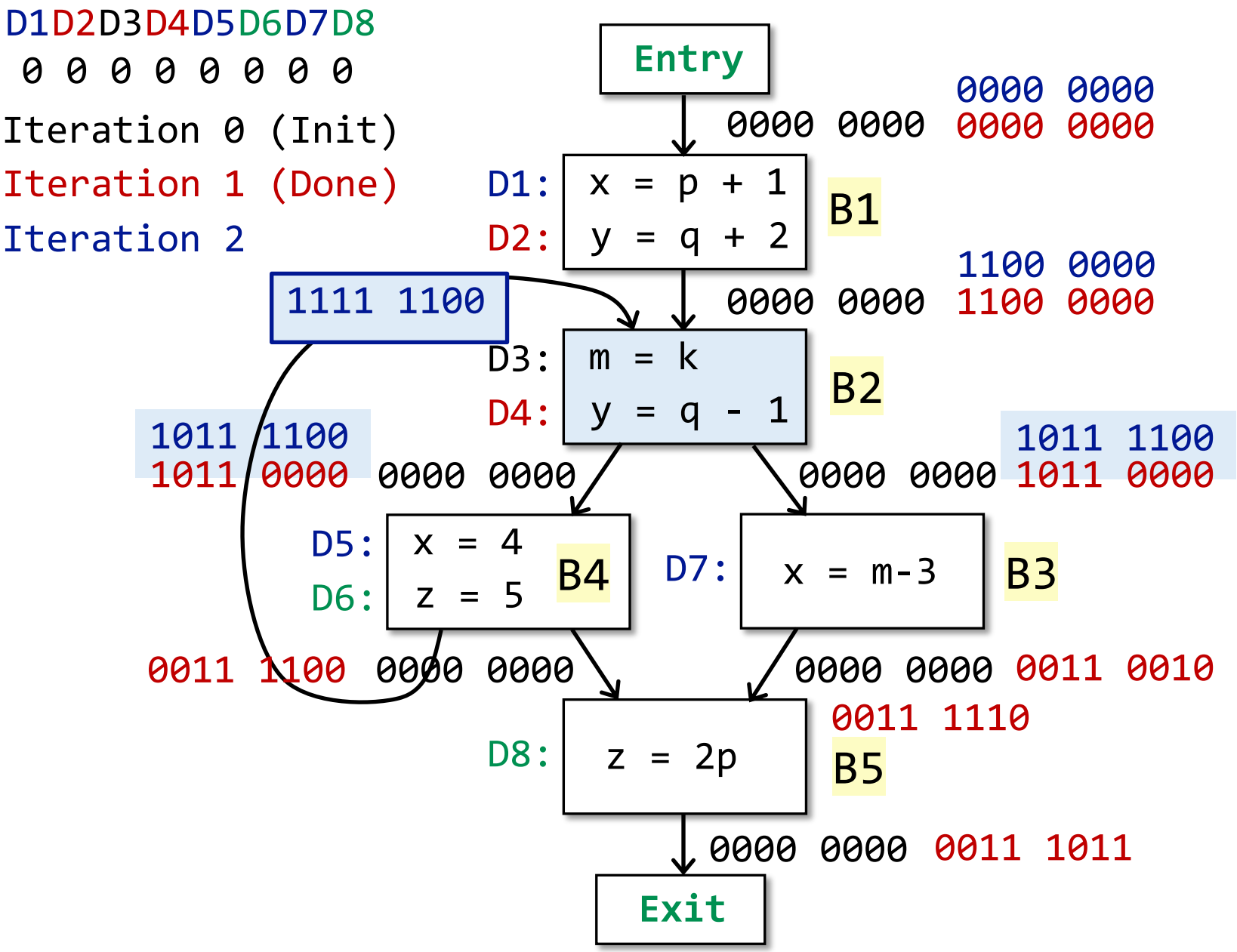

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1: x = p + 1
D2: y = q + 2
B1
1100 0000
1100 0000
0000 0000
D3: m = k
D4: y = q - 1
B2
1011 0000
0000 0000
0000 0000
1011 0000
D5: x = 4
D6: z = 5
B4
D7: x = m-3
B3
0011 1100
0000 0000
0000 0000
0011 0010
0011 1110
D8: z = 2p
B5
0000 0000
0011 1011
Exit

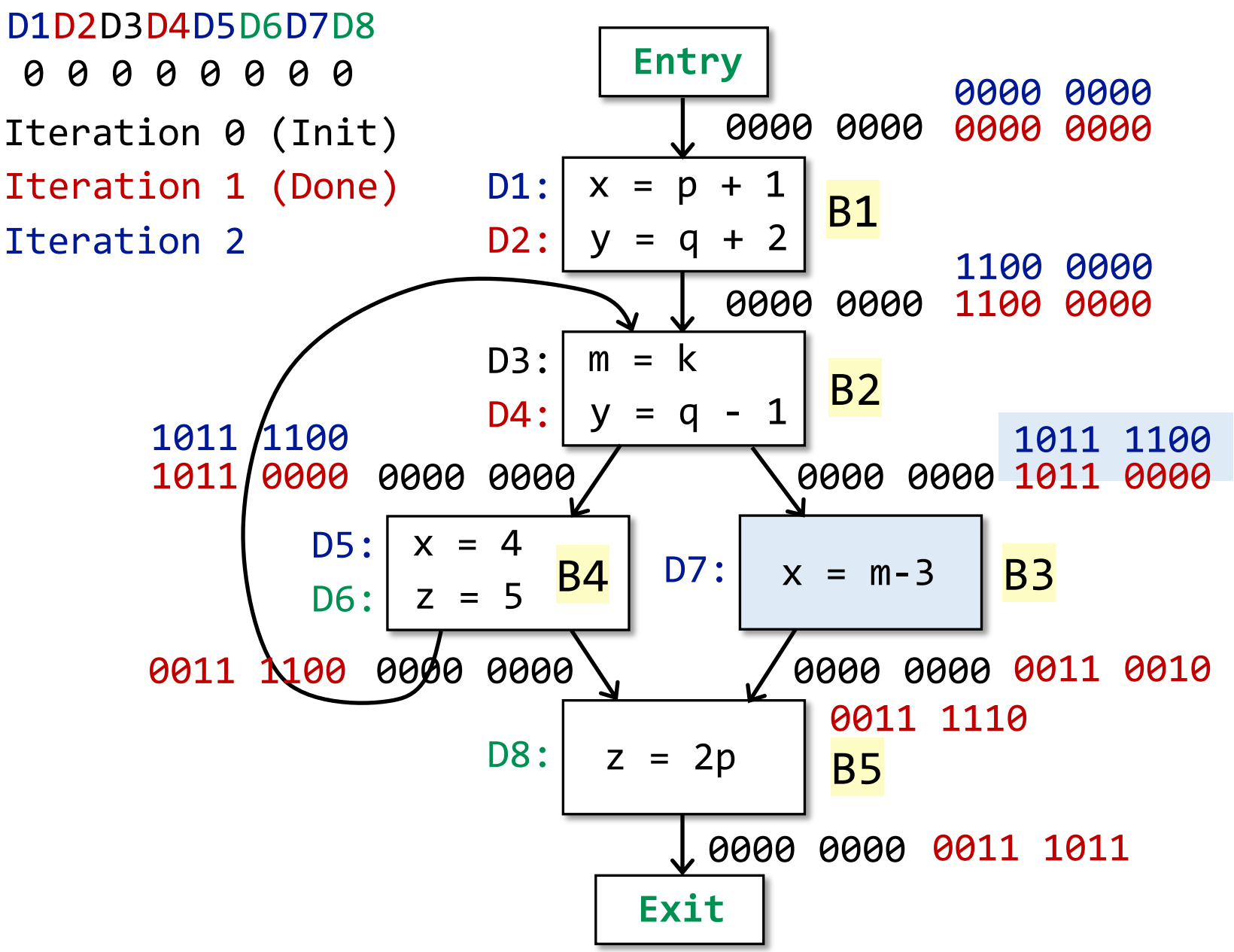

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 0000
0000 0000
0000 0000
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
0000 0000
0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

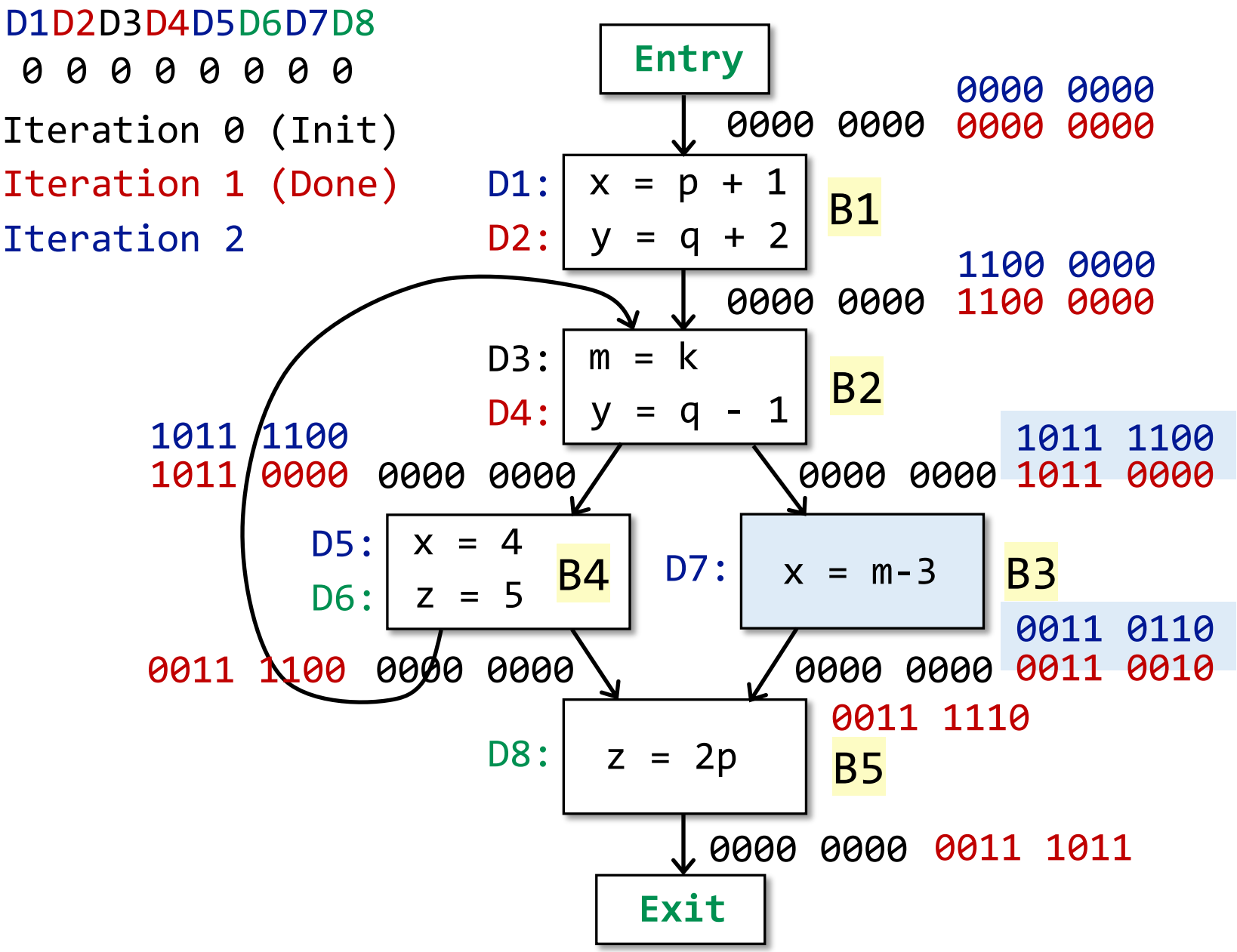

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1100 0000
0000 0000
U
D3:
m = k
D4:
y = q - 1
B2
1011 0000
0000 0000
0000 0000
0000 0000 1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
0000 0000 0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000 0011 1011
Exit

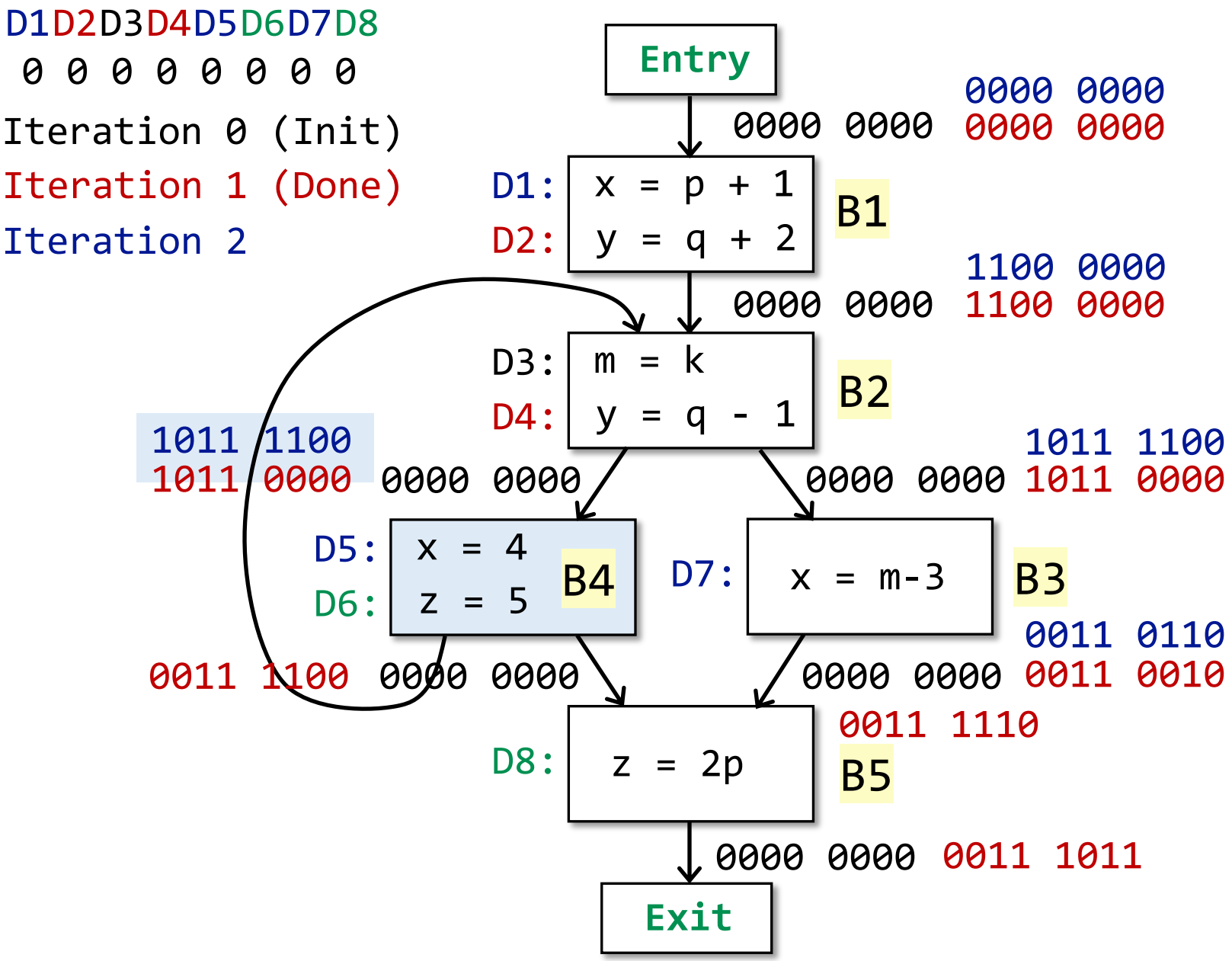

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1100 0000
1111 1100
U
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 0000
0000 0000
0000 0000 1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
0000 0000 0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000 0011 1011
Exit

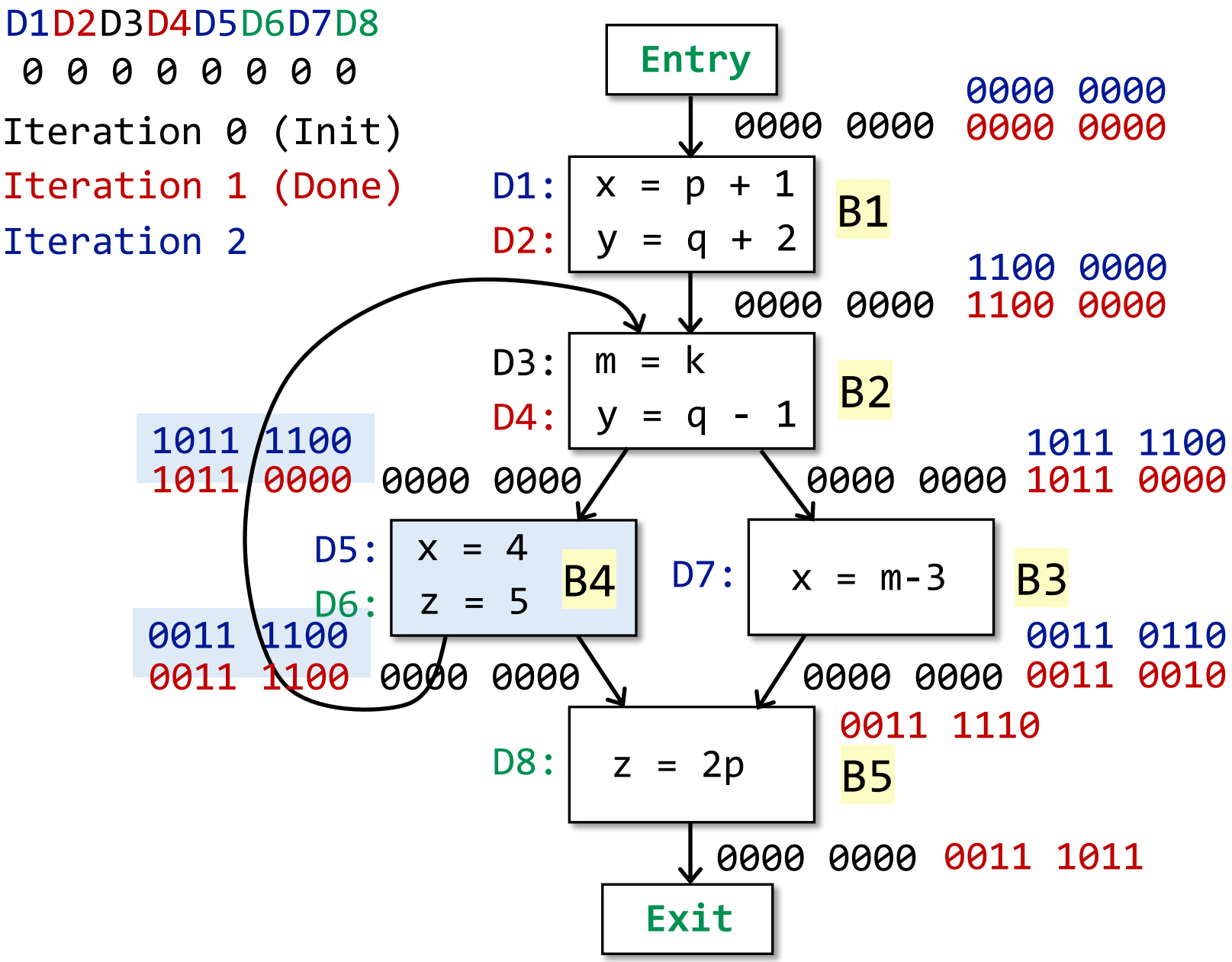

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1111 1100
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 0000
0000 0000
0000 0000
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
0000 0000
0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

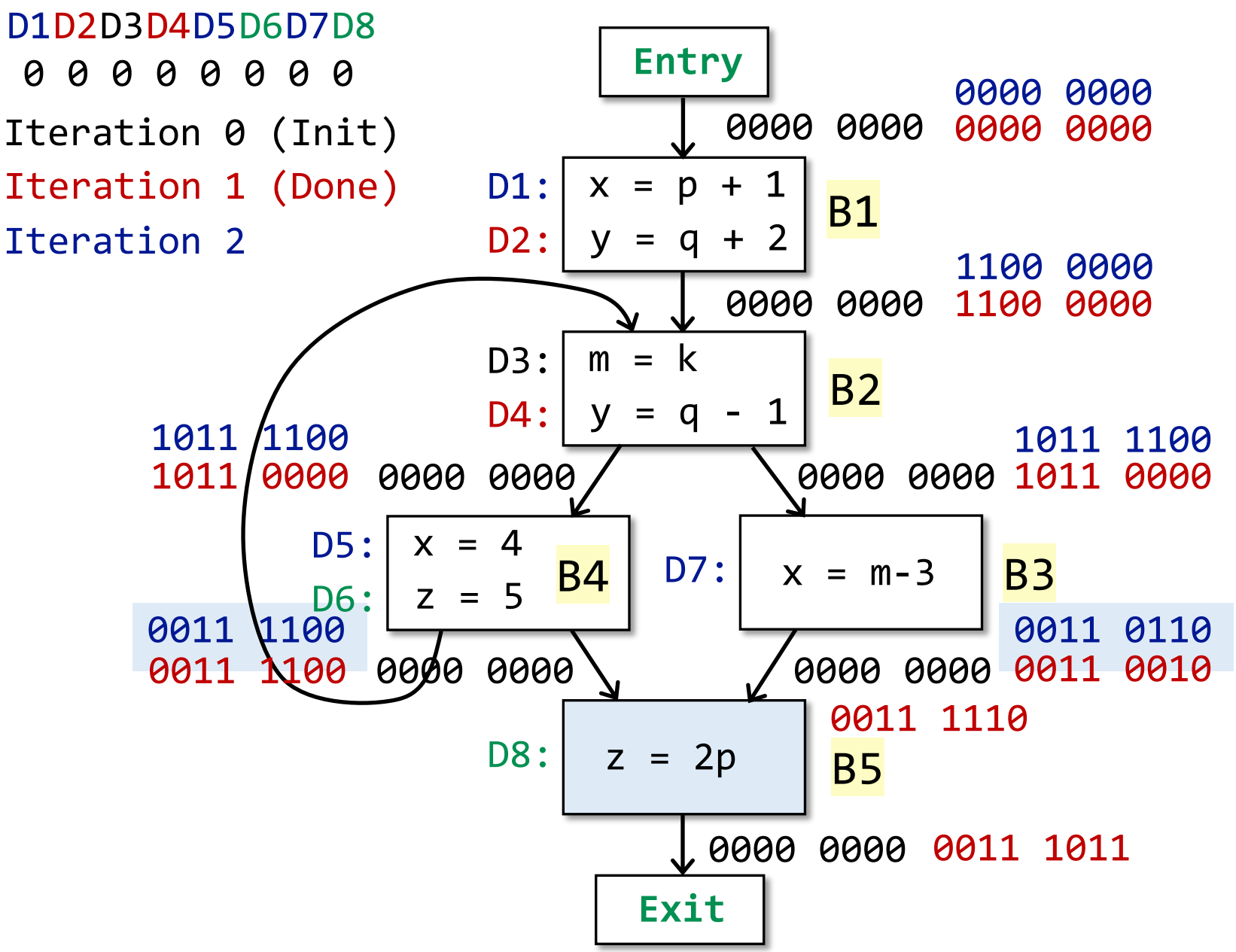

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1111 1100
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
0000 0000
0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

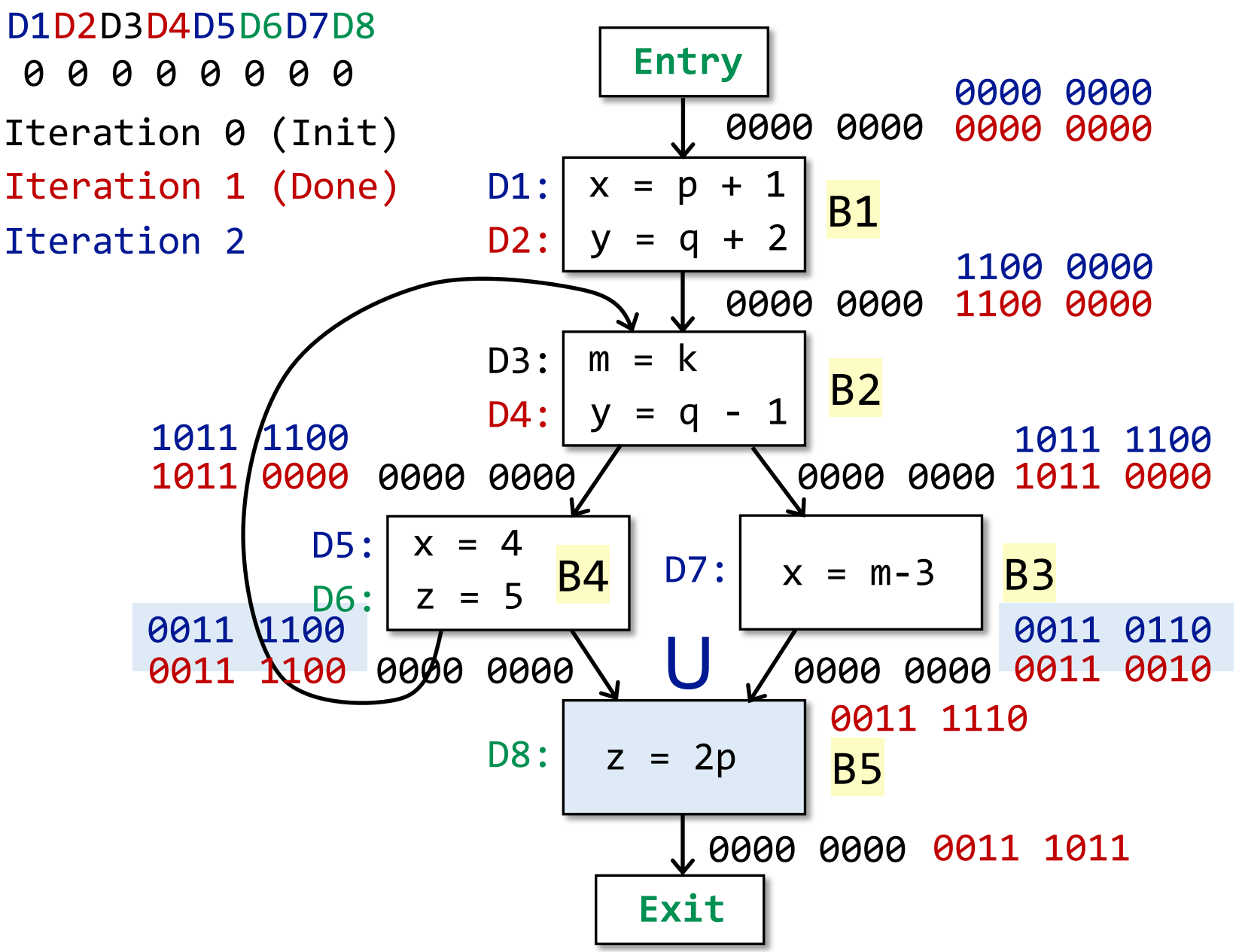

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0000 0000
0000 0000
0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

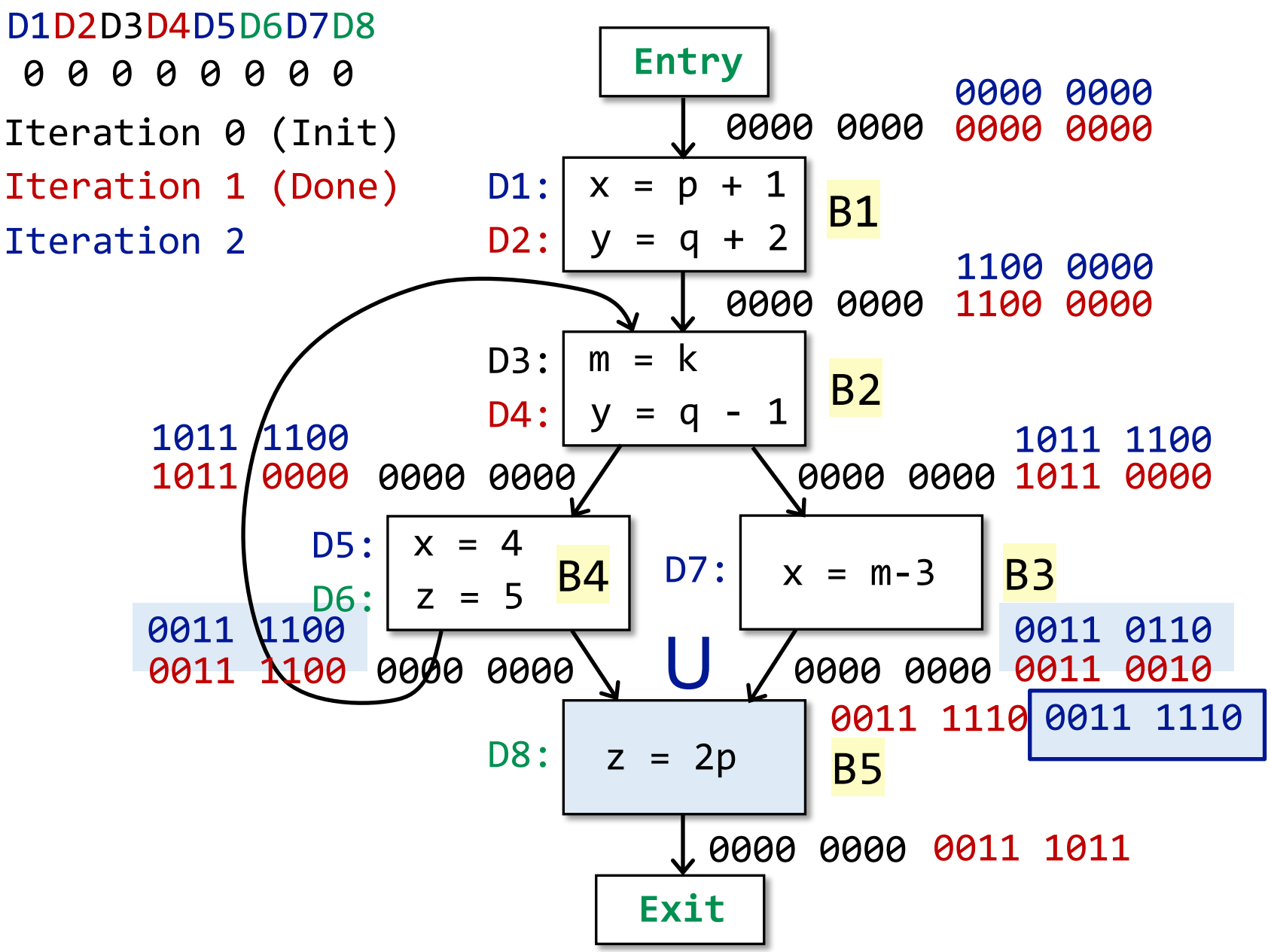

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 0110
0011 0010
0011 1100
0000 0000
0000 0000
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

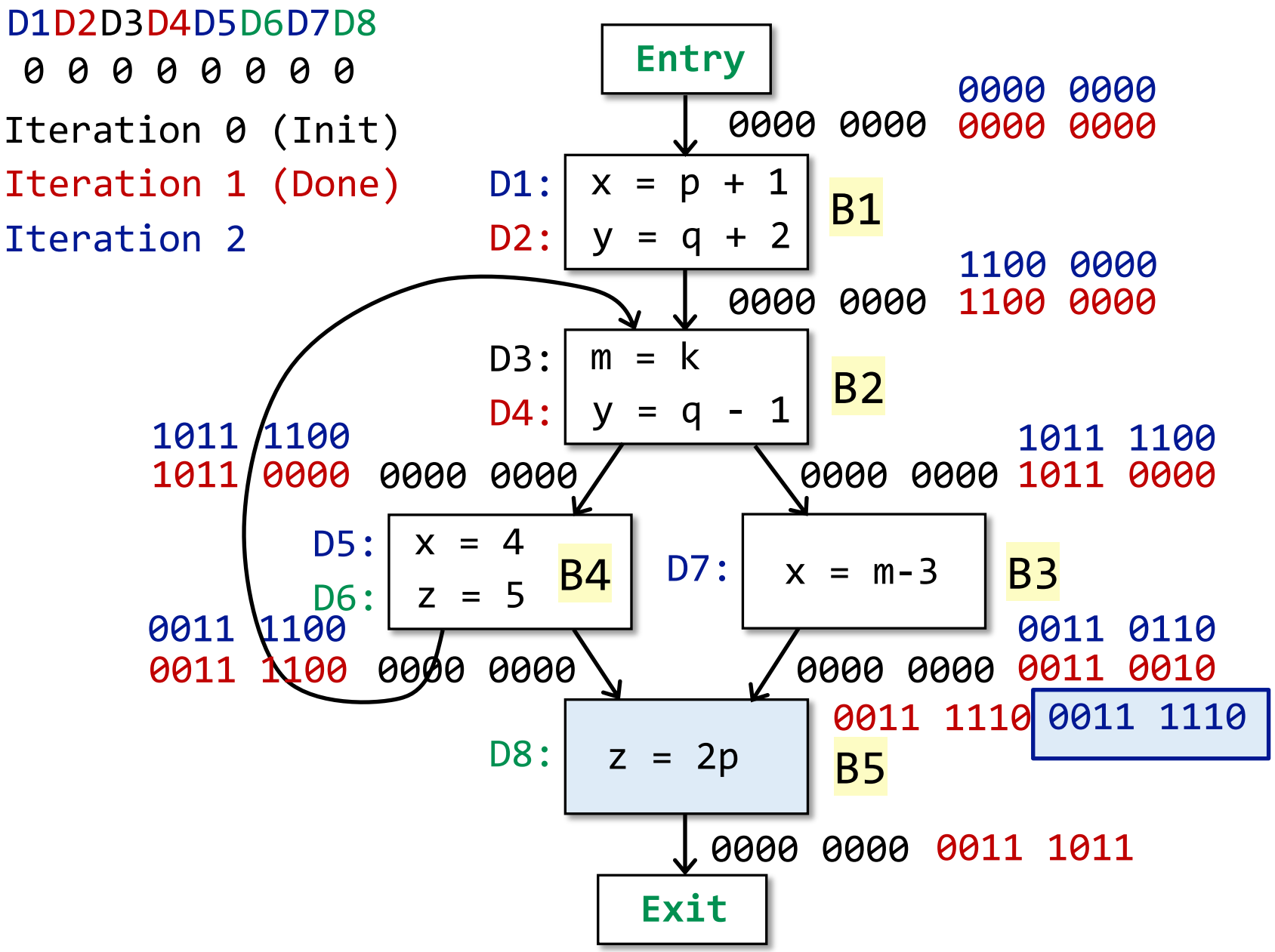

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 0110
0011 1100
0000 0000
0000 0000
0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

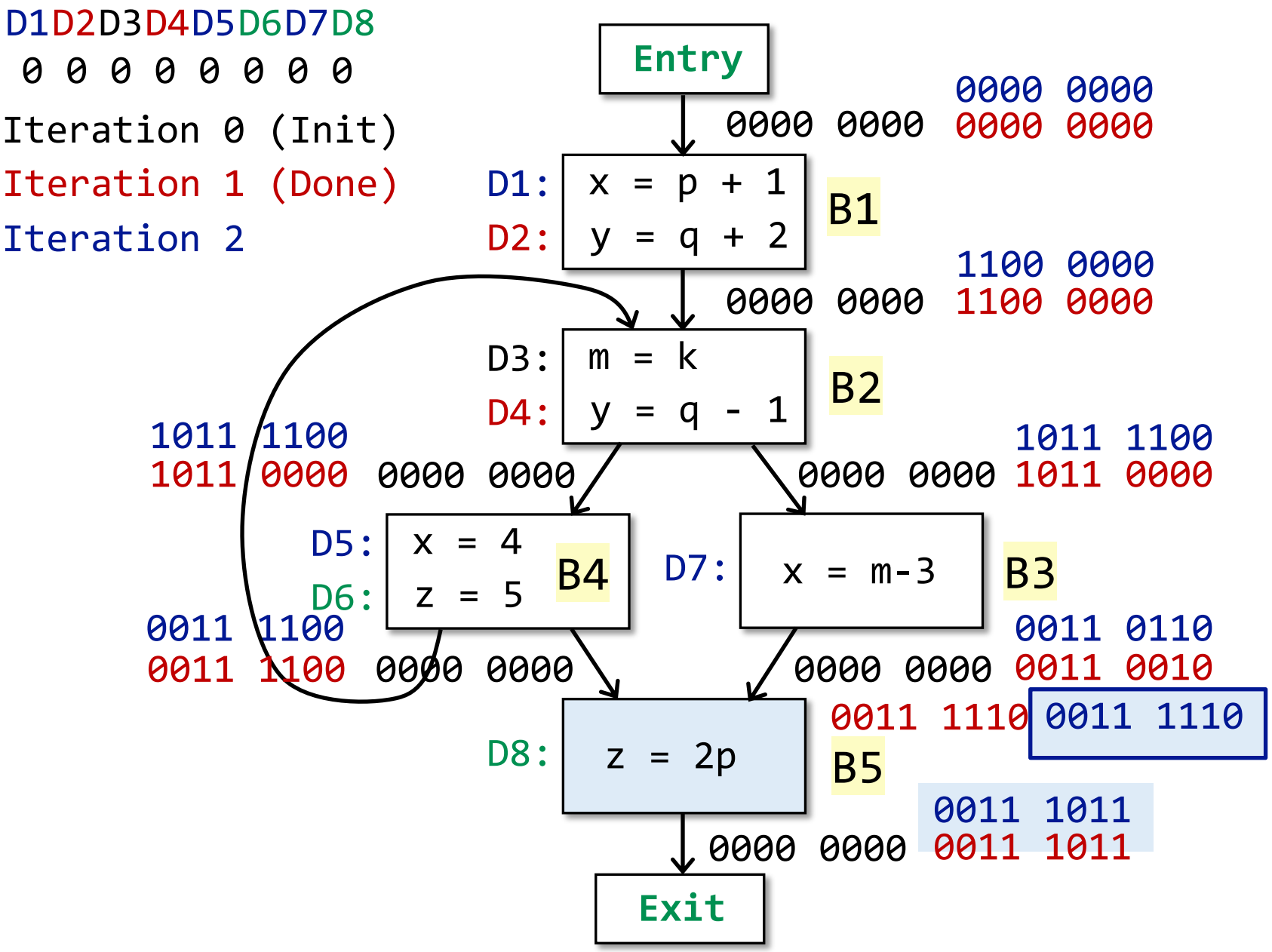

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

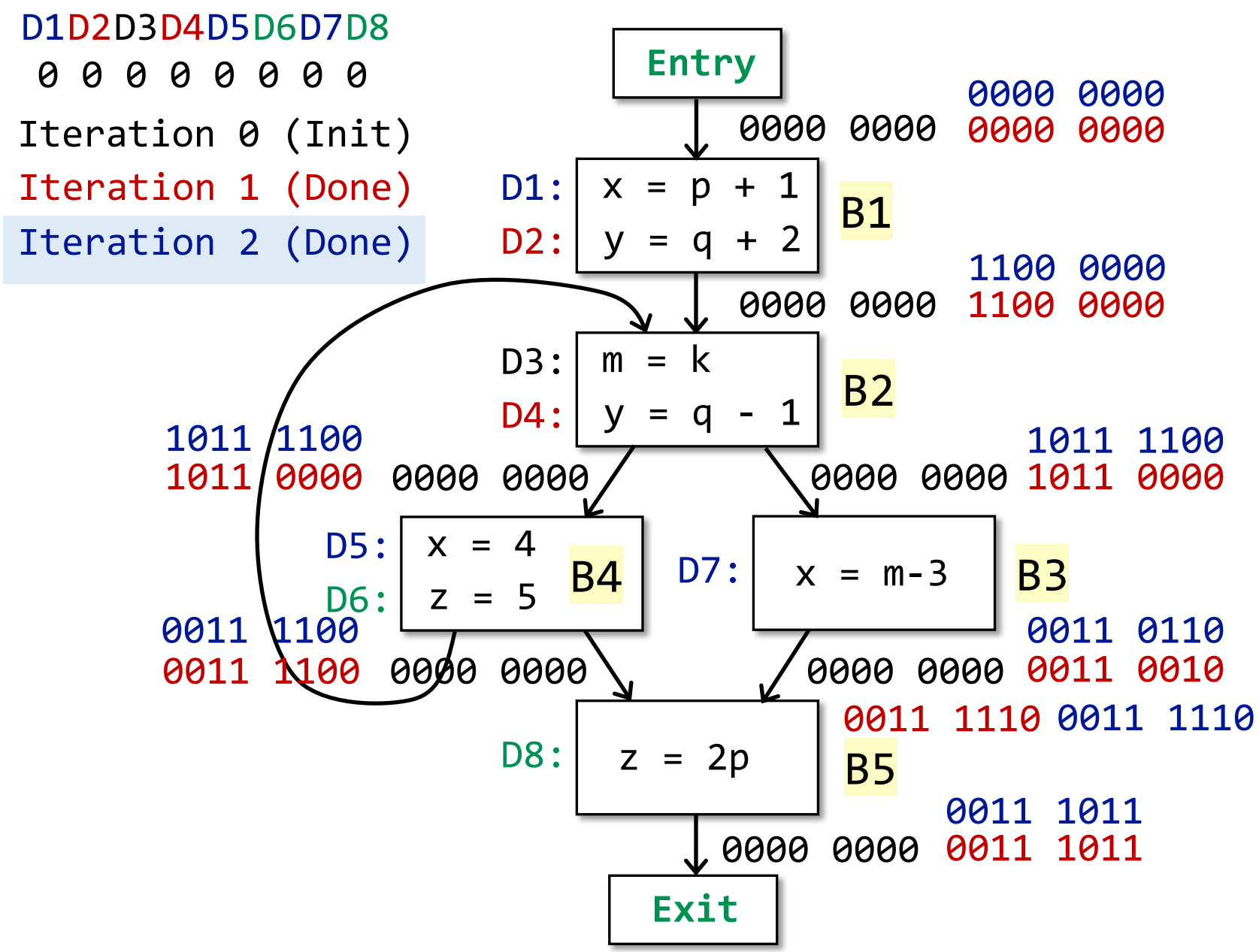

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

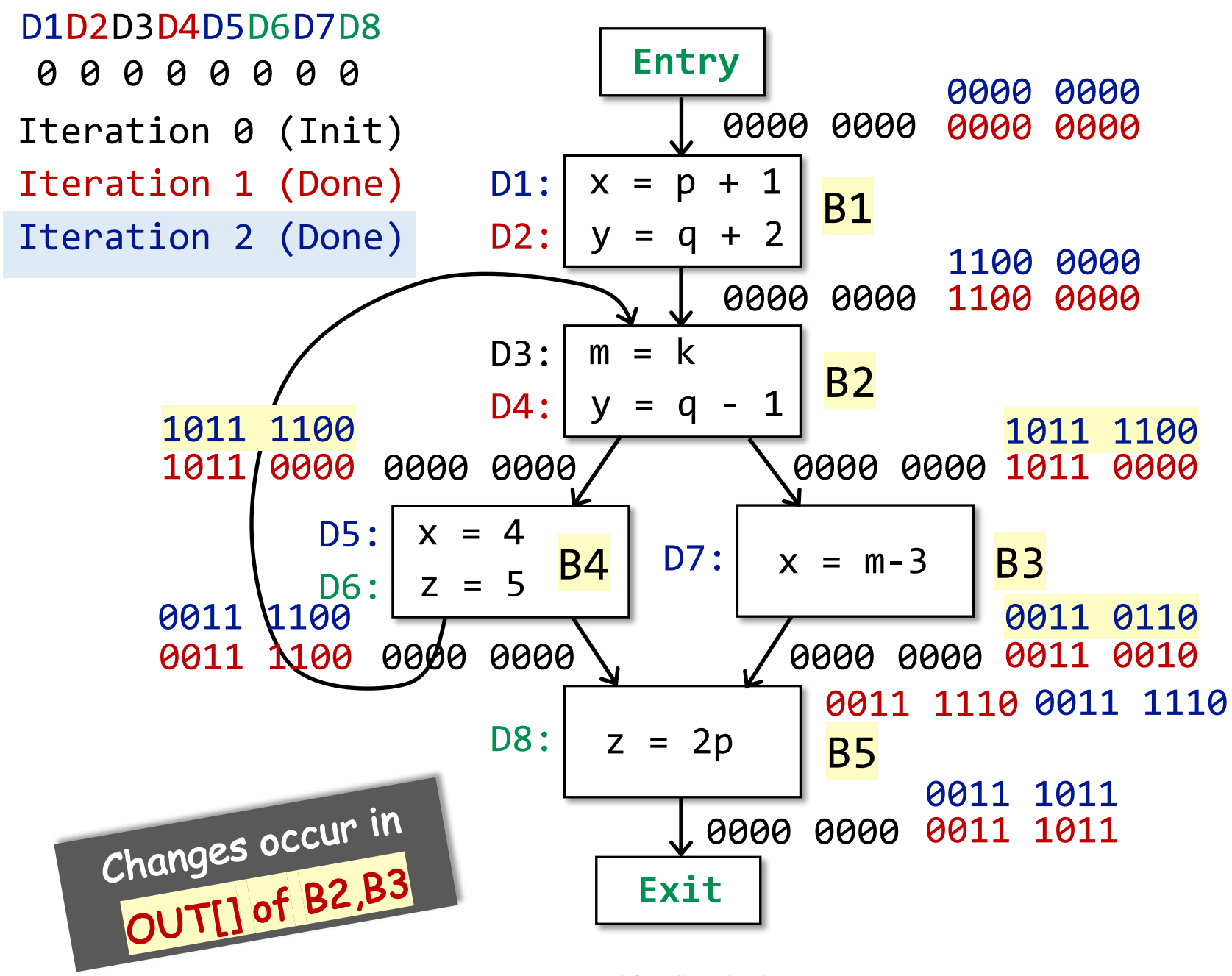

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
U
0000 0000
0011 0110
0011 0010
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

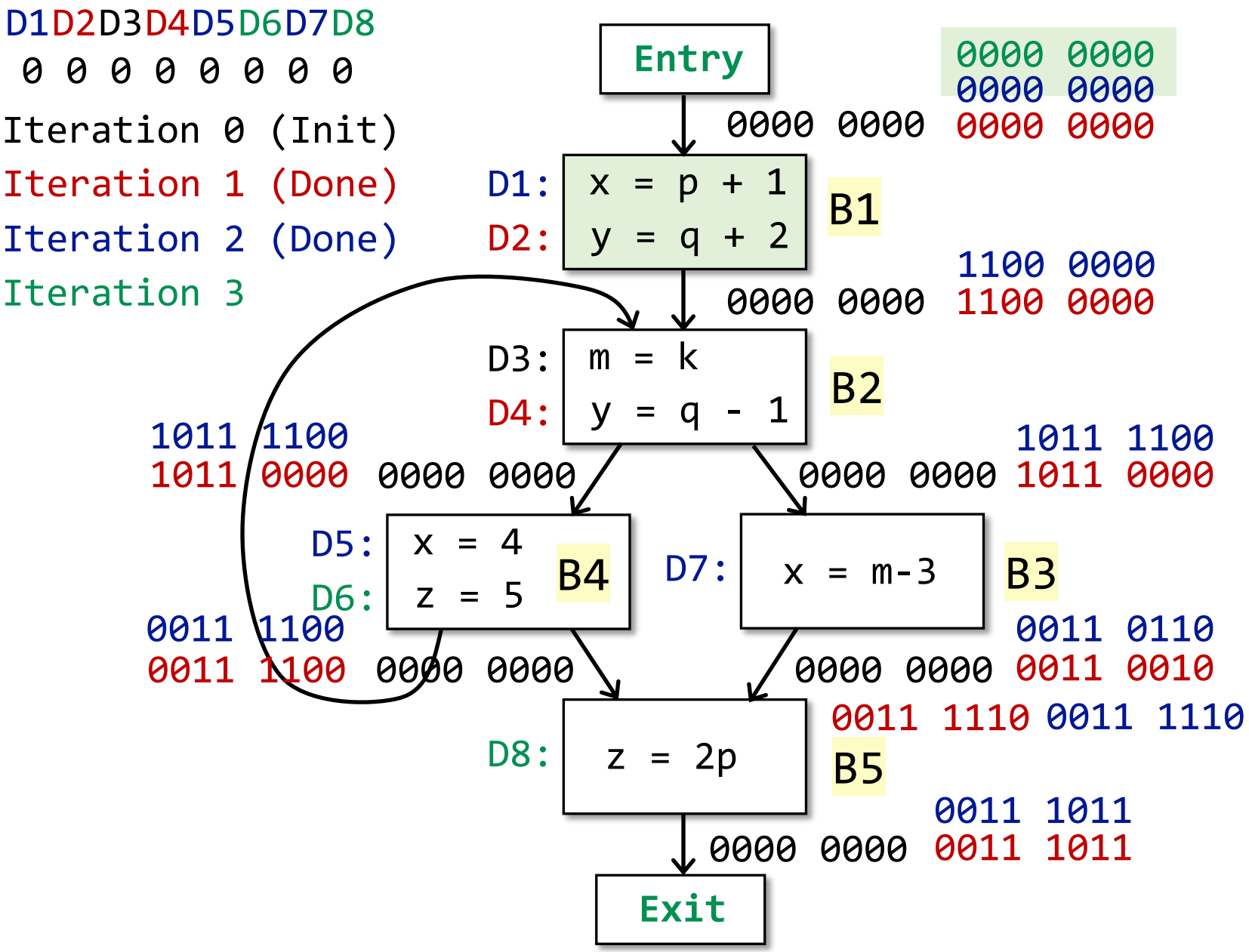

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
U
0000 0000
0011 0110
0011 0010
0011 1110
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

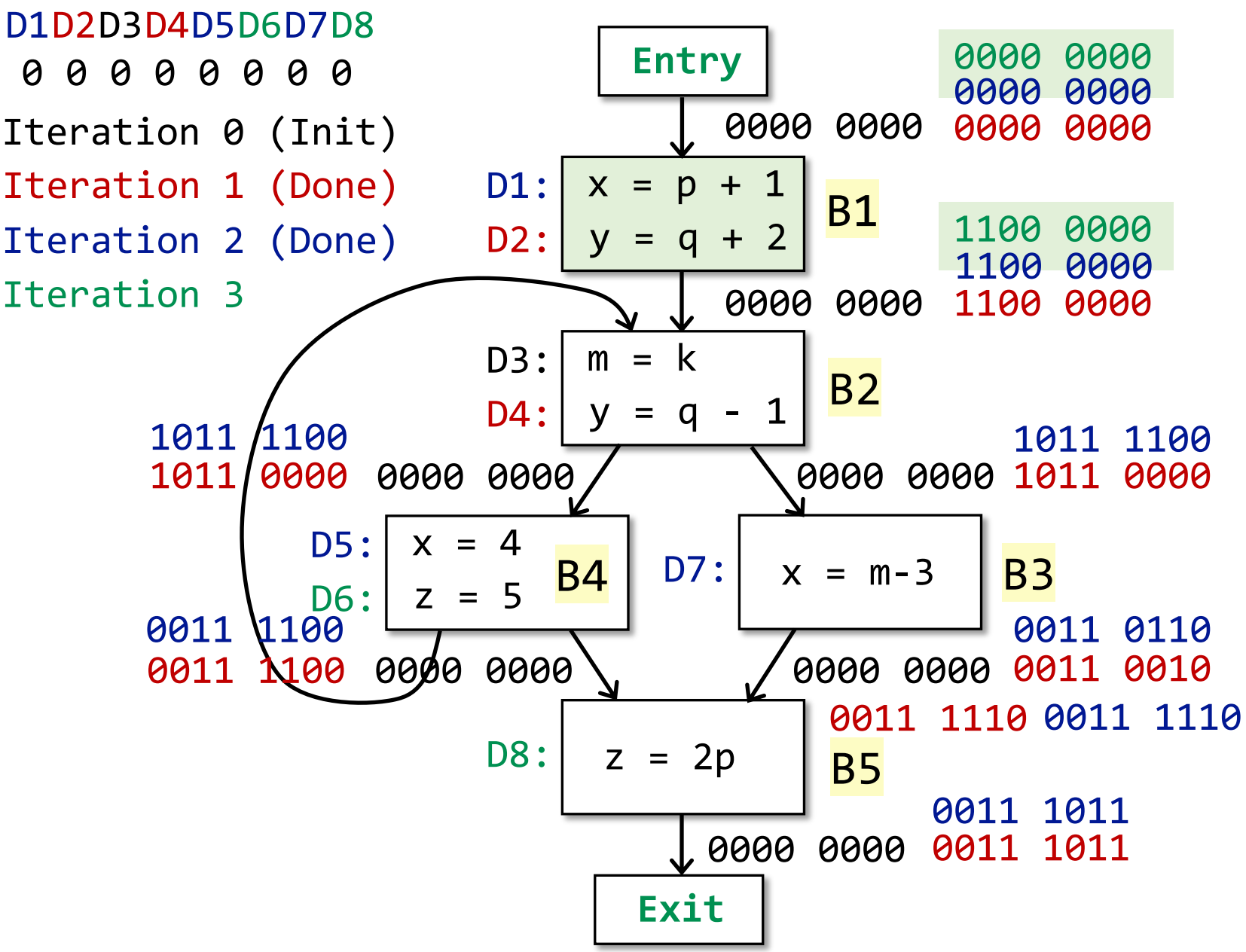

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110
0011 1110
D8:
z = 2p
B5
0000 0000
0011 1011
Exit

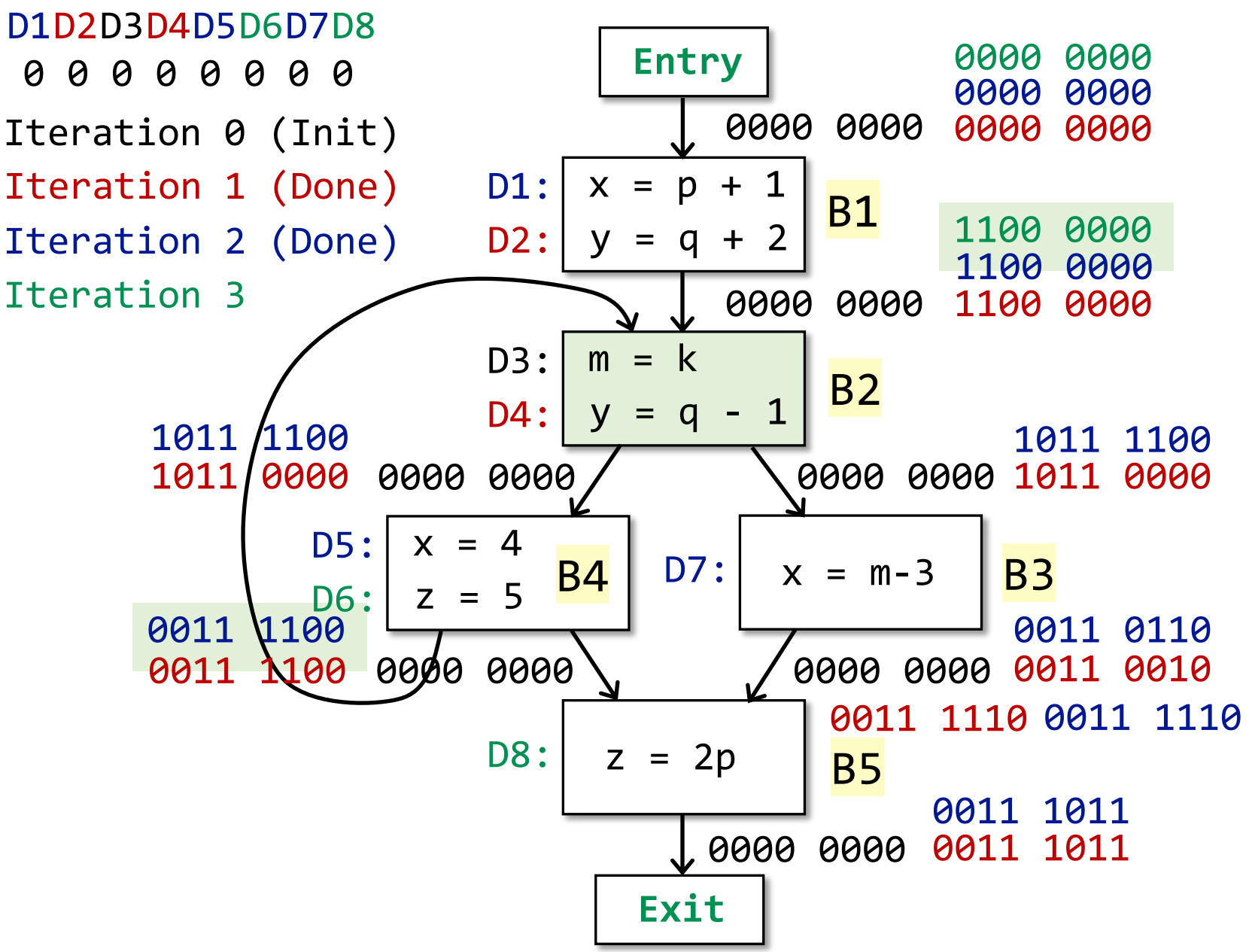

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110
0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0000 0000
Exit

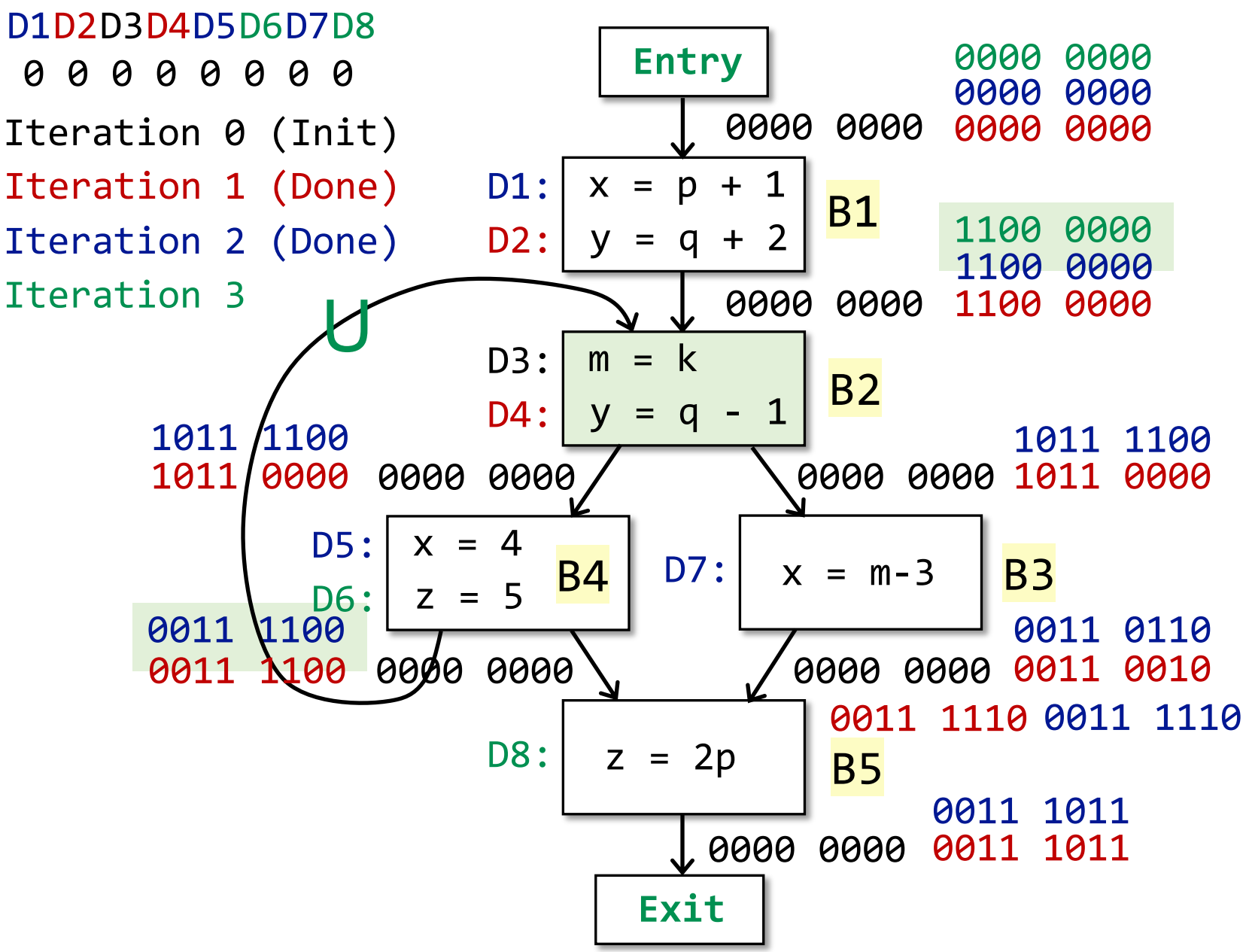

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Entry
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0011 0110
0000 0000
0011 0010
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0000 0000
0011 1011
Exit

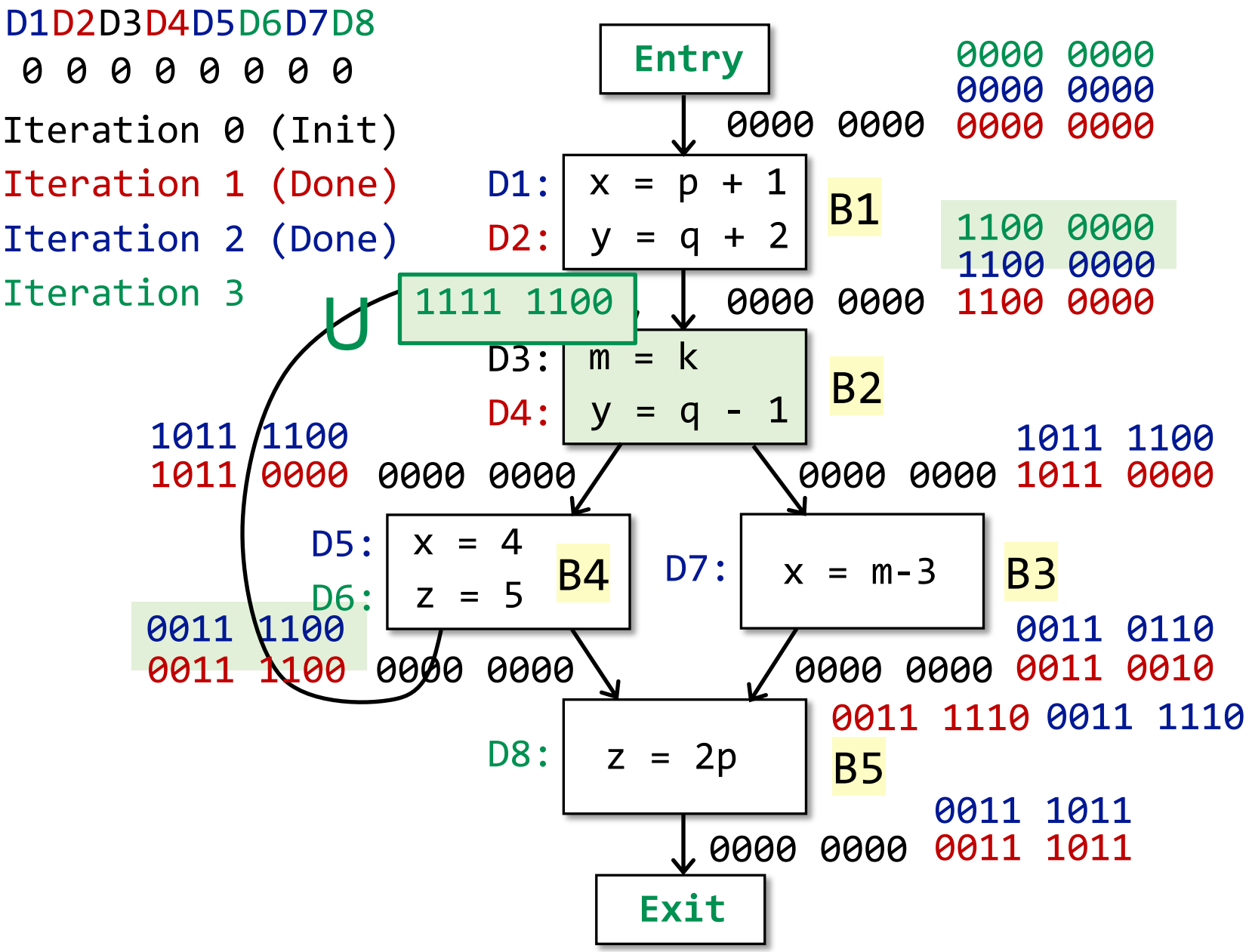

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Entry
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0011 0110
0000 0000
0011 0010
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0000 0000
0011 1011
Exit
Changes occur in
OUT[] of B2,B3

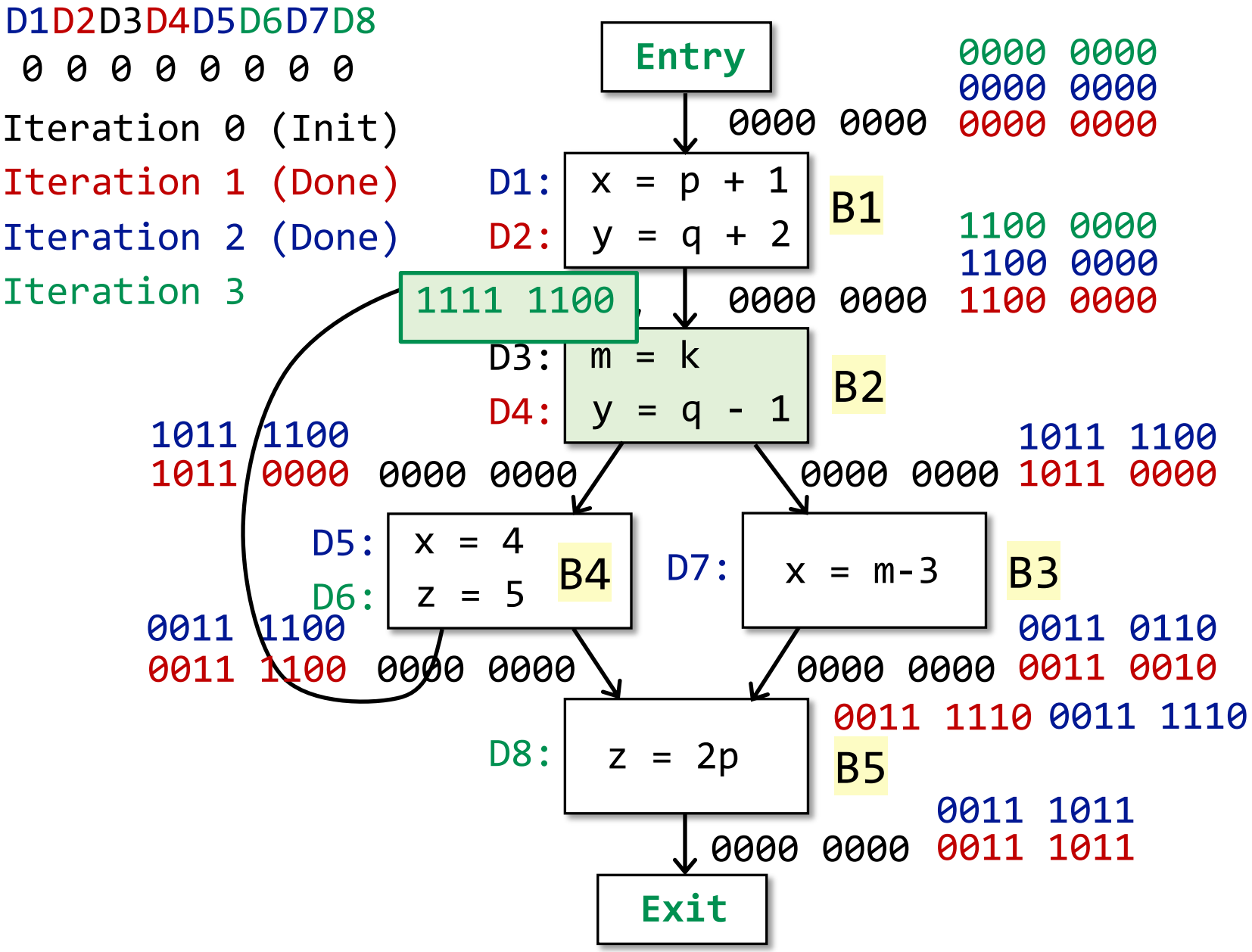

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0011 0110
0000 0000
0011 0010
0011 1110
0011 1110
D8:
z = 2p
B5
0011 1011
0000 0000
0011 1011
Exit

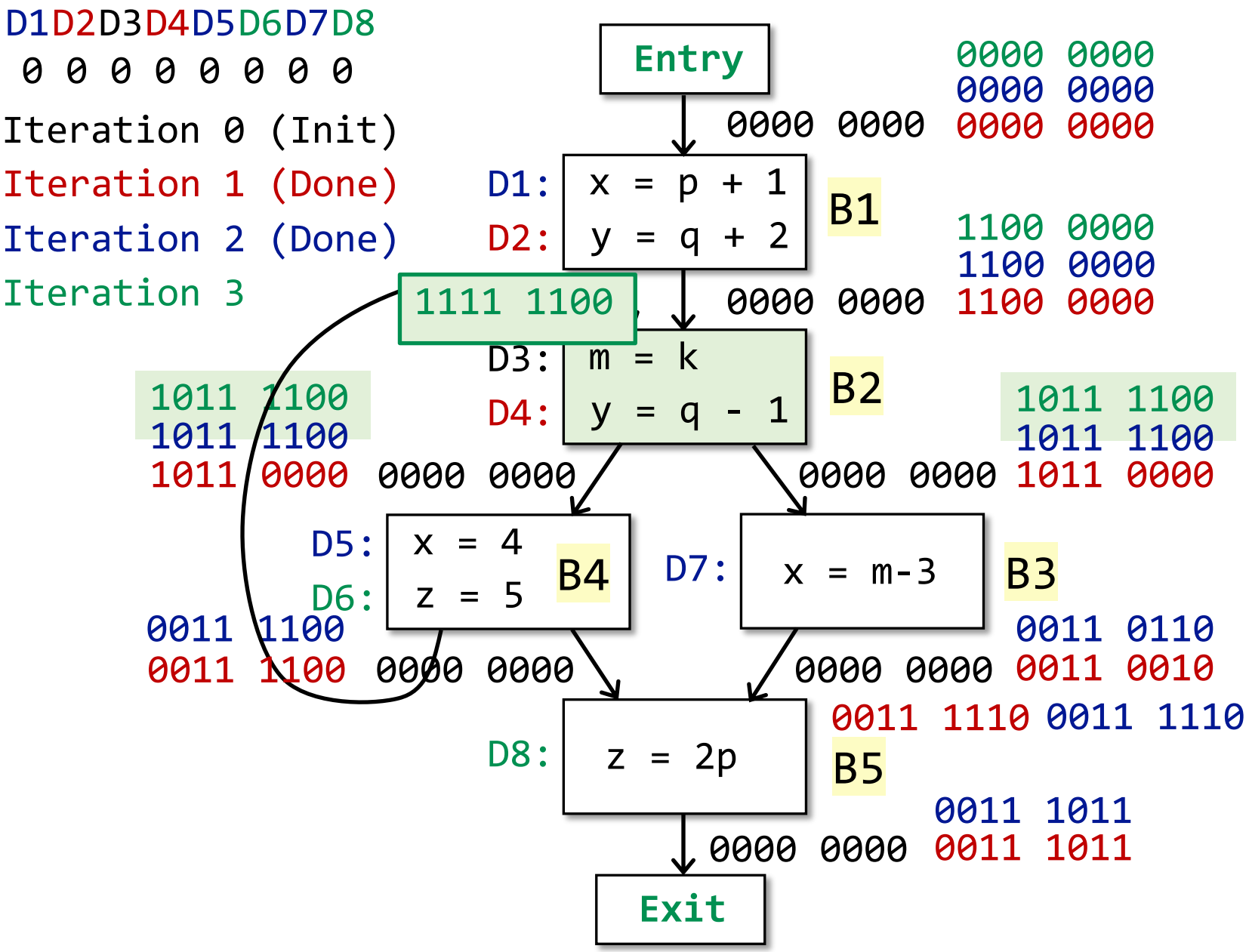

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110
0011 1110
D8:
z = 2p
B5
0011 1011
0000 0000
0011 1011
Exit

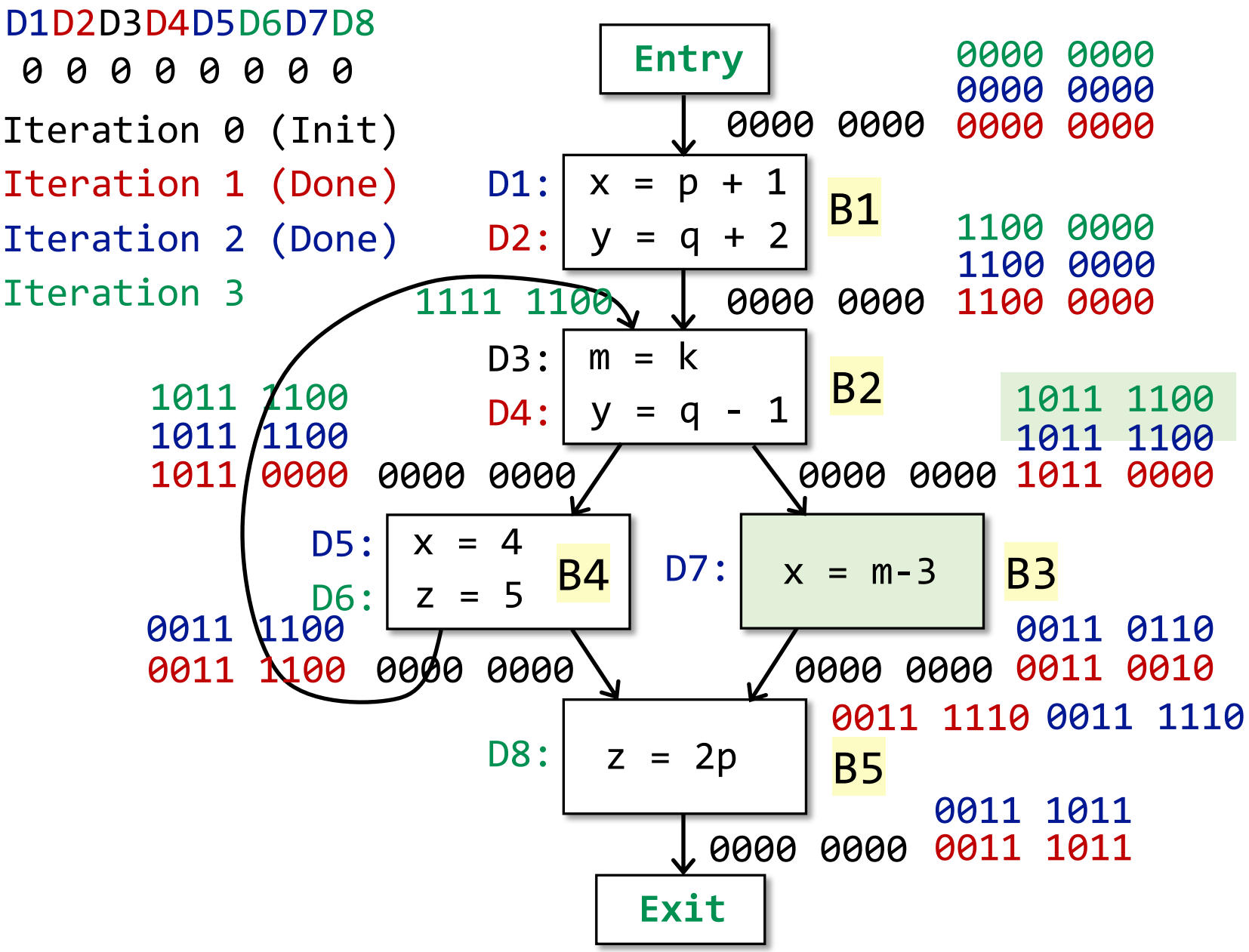

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0000 0000
0011 1011
Exit

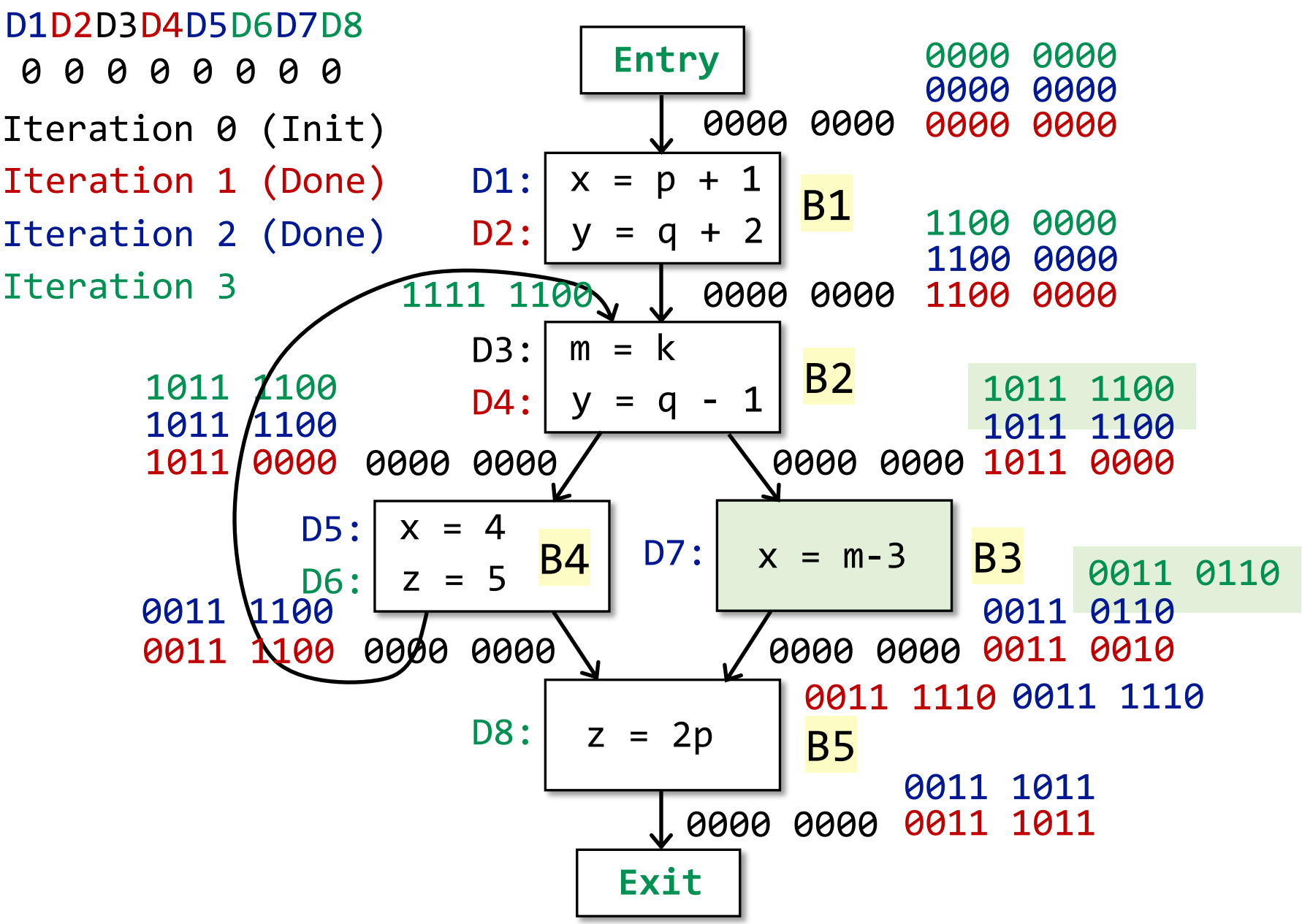

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1100 0000
0000 0000
1100 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0000 0000
0011 1011
Exit

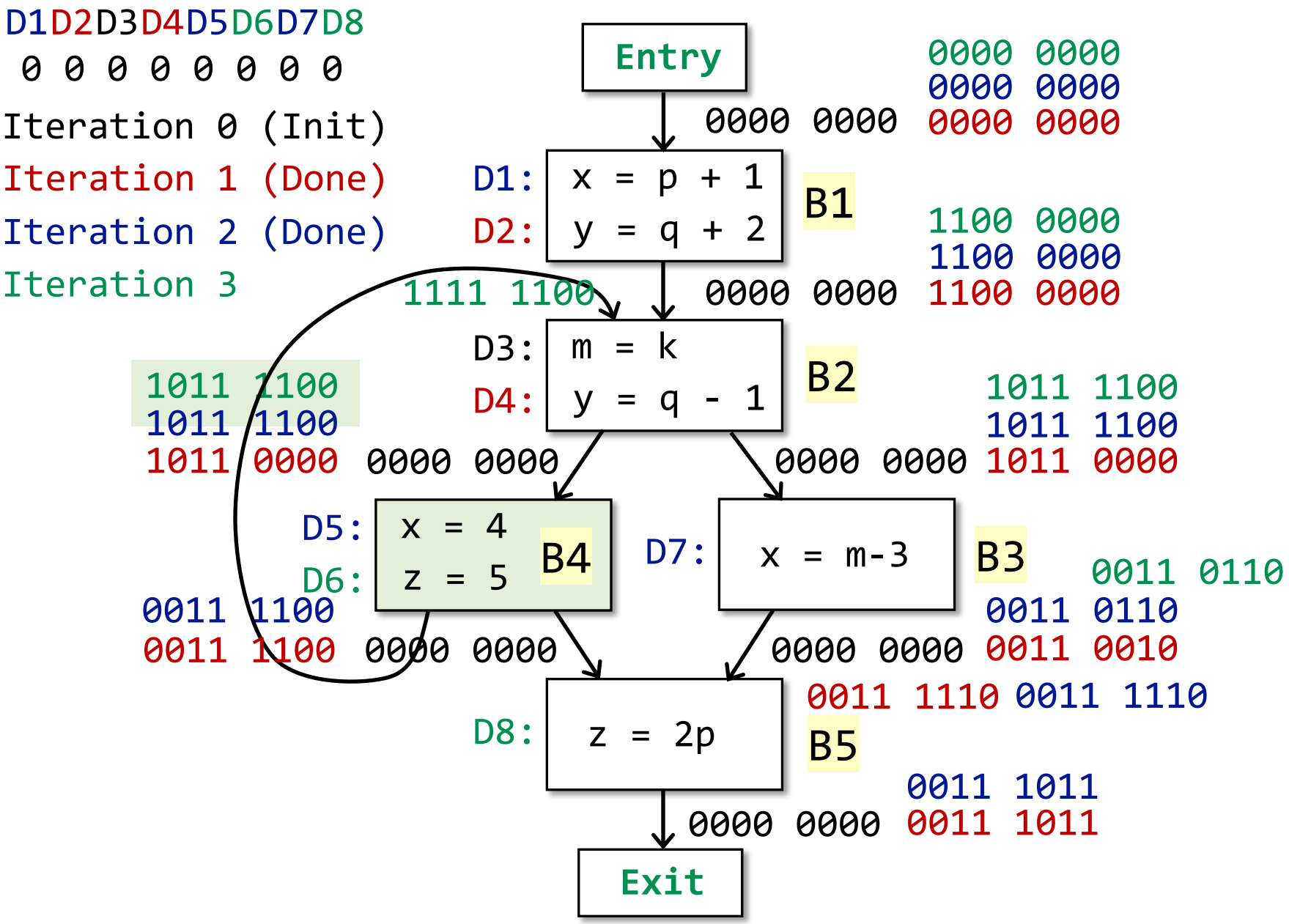

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
U
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0000 0000
0011 1011
Exit

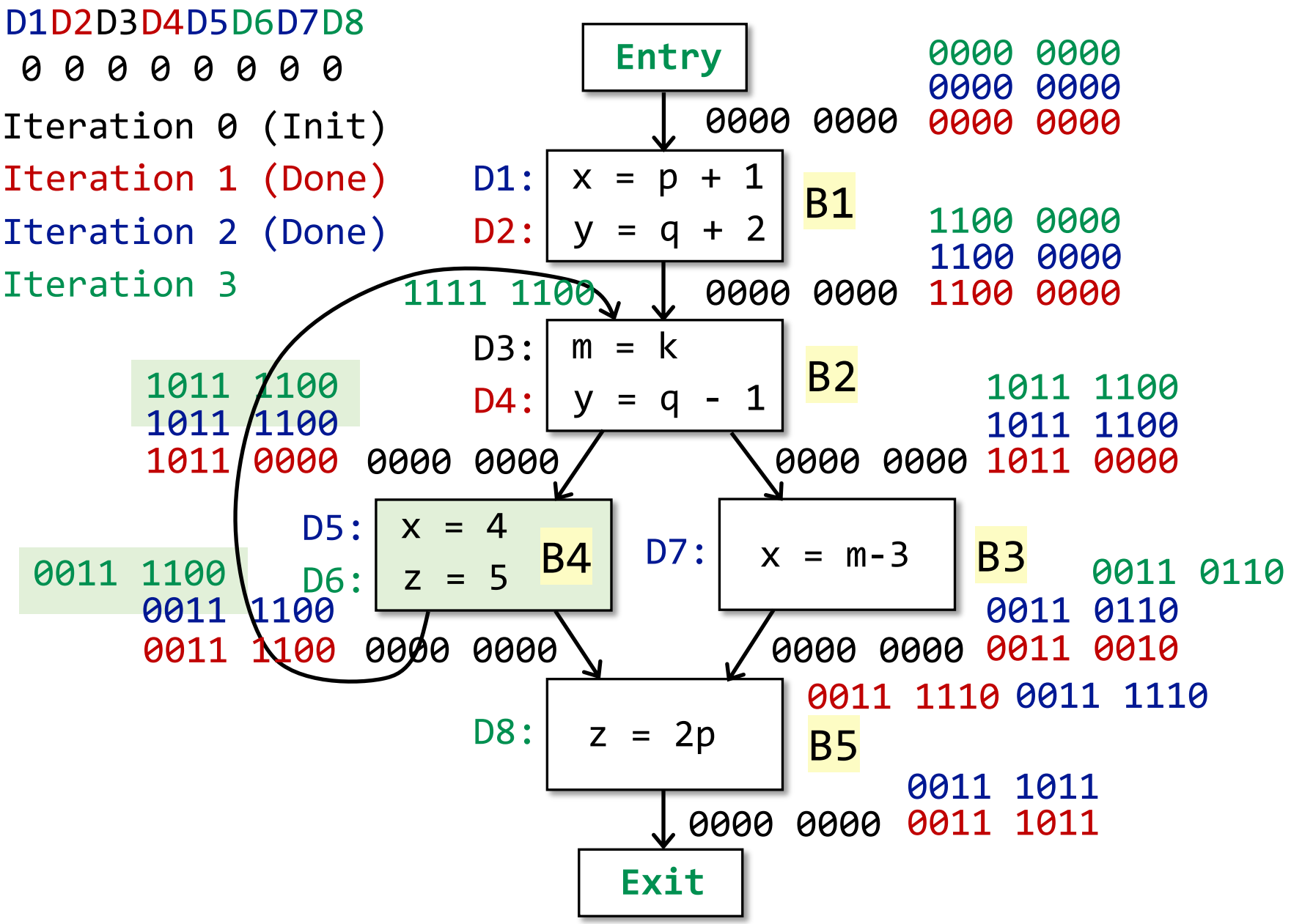

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 0000
0000 0000
0000 0000
1011 1100
1011 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0000 0000
0011 0110
0011 0010
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0000 0000
0011 1011
Exit

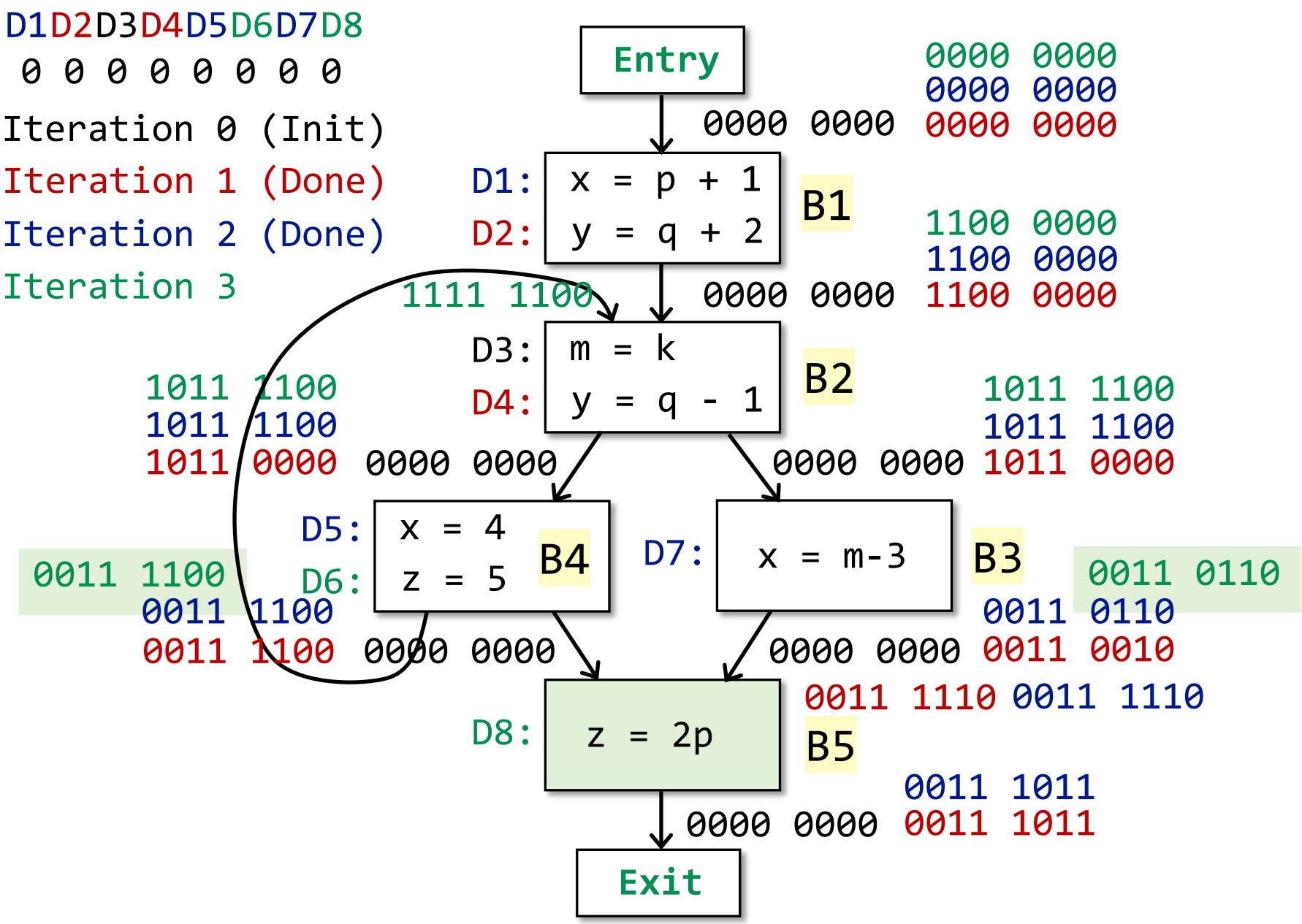

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0000 0000
0011 0110
0011 0010
0000 0000
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0000 0000
Exit

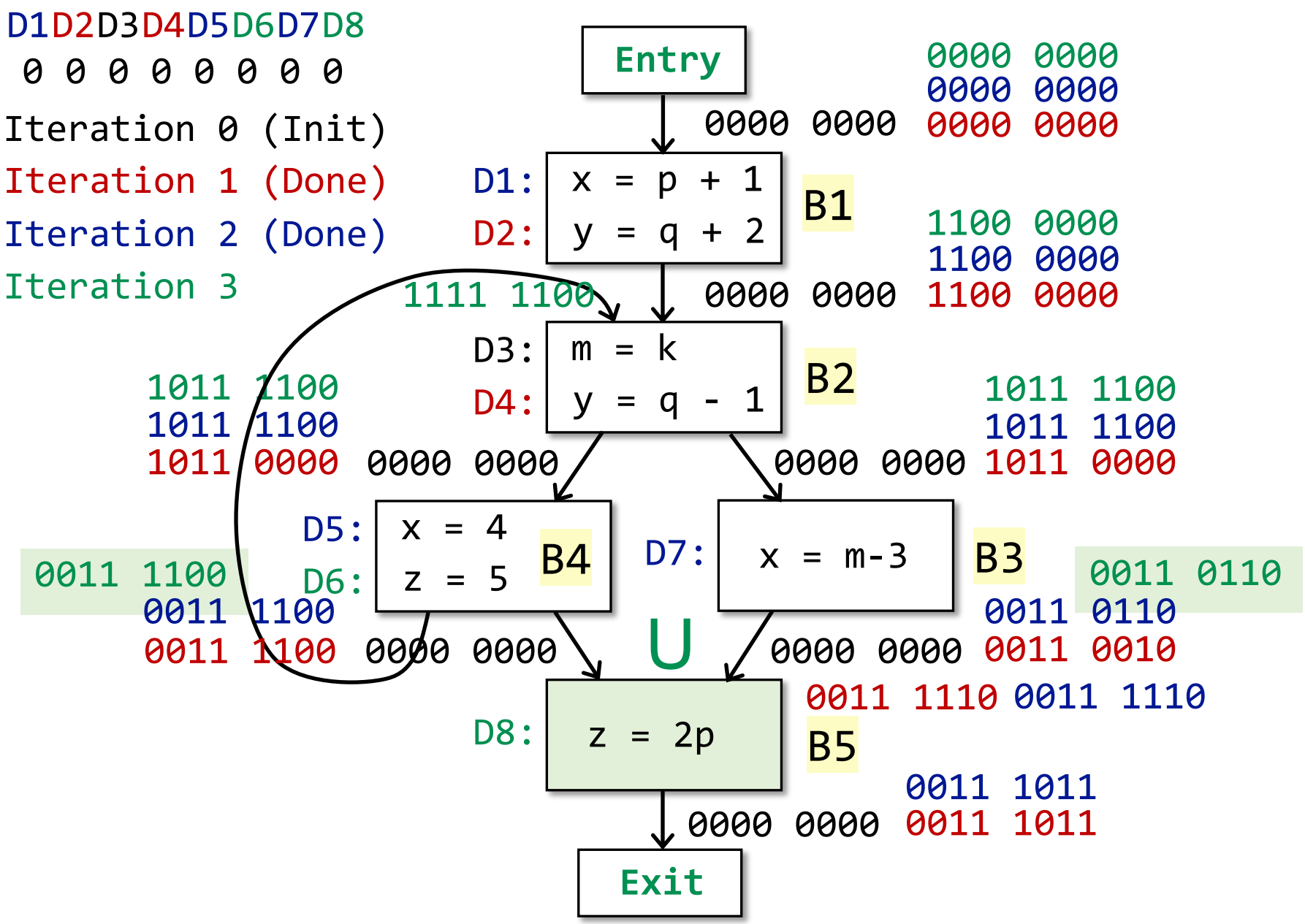

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0011 0110
0011 0010
0000 0000
0000 0000
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0000 0000
Exit

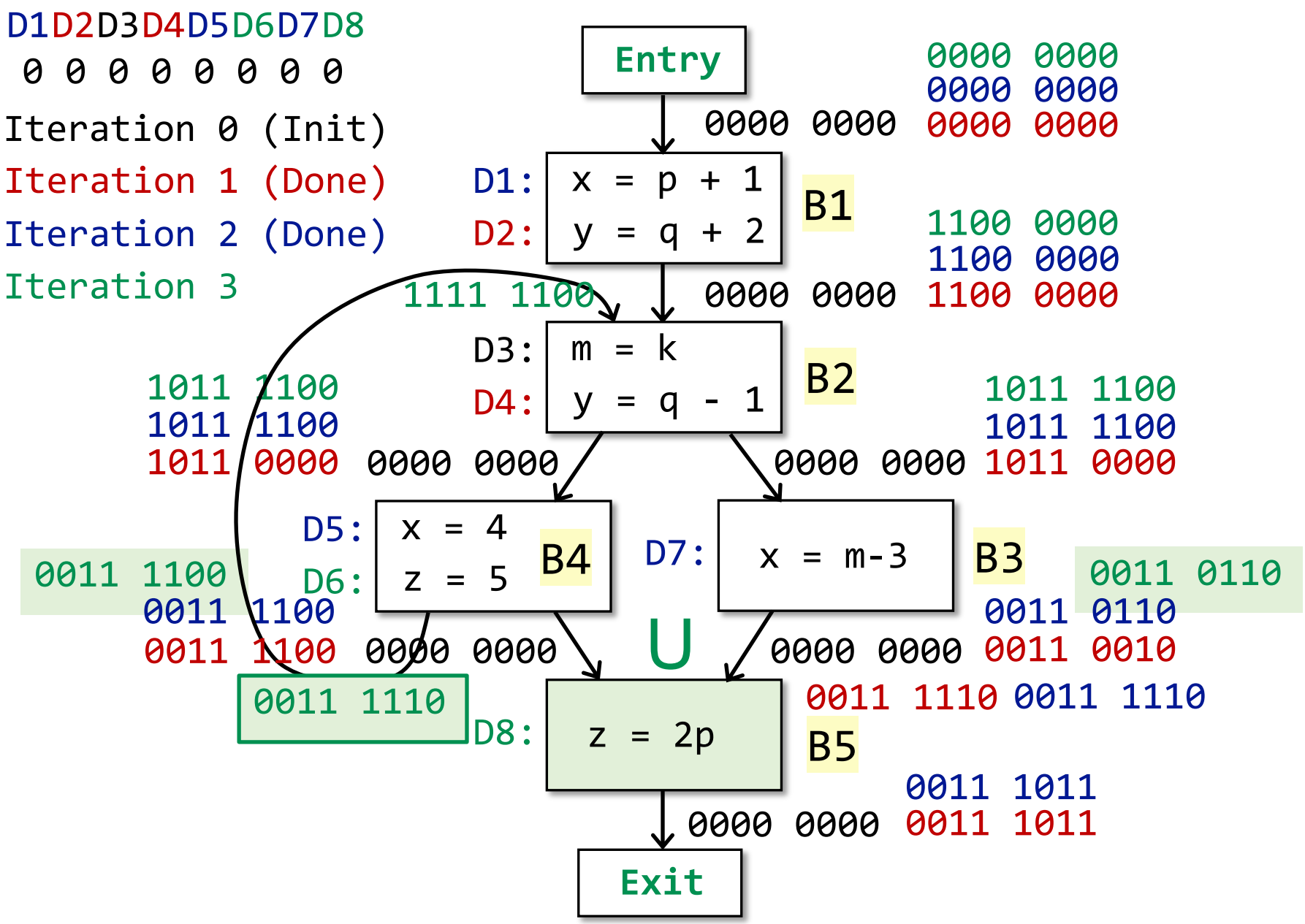

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 0110
0011 1100
0011 1100
0011 0110
0011 0010
0000 0000
0000 0000
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0000 0000
Exit

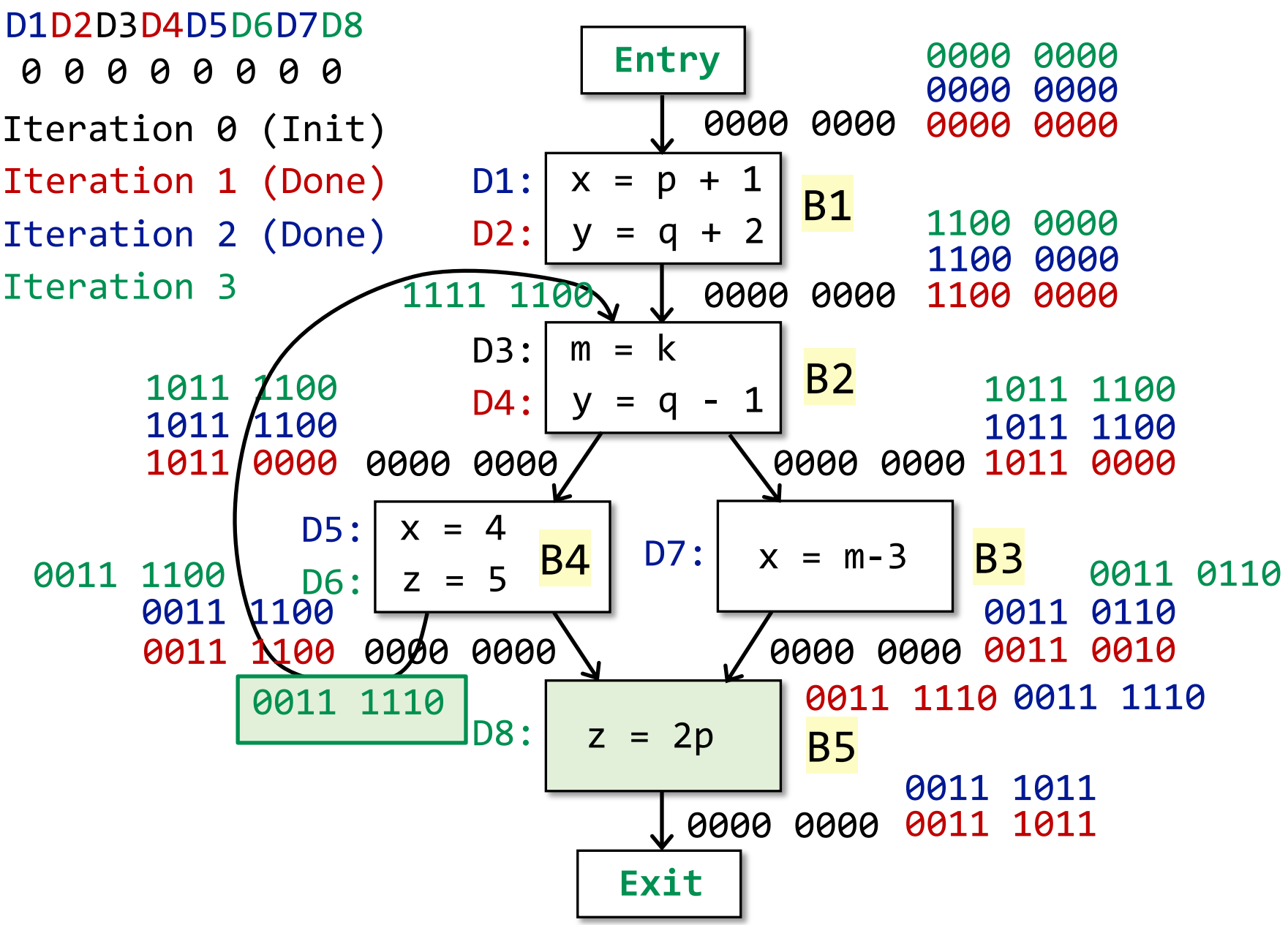

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 0110
0011 1100
0011 1100
0011 0110
0011 0010
0000 0000
0000 0000
D8:
z = 2p
B5
0011 1110 0011 1110
0011 1011
0011 1011
0000 0000
Exit

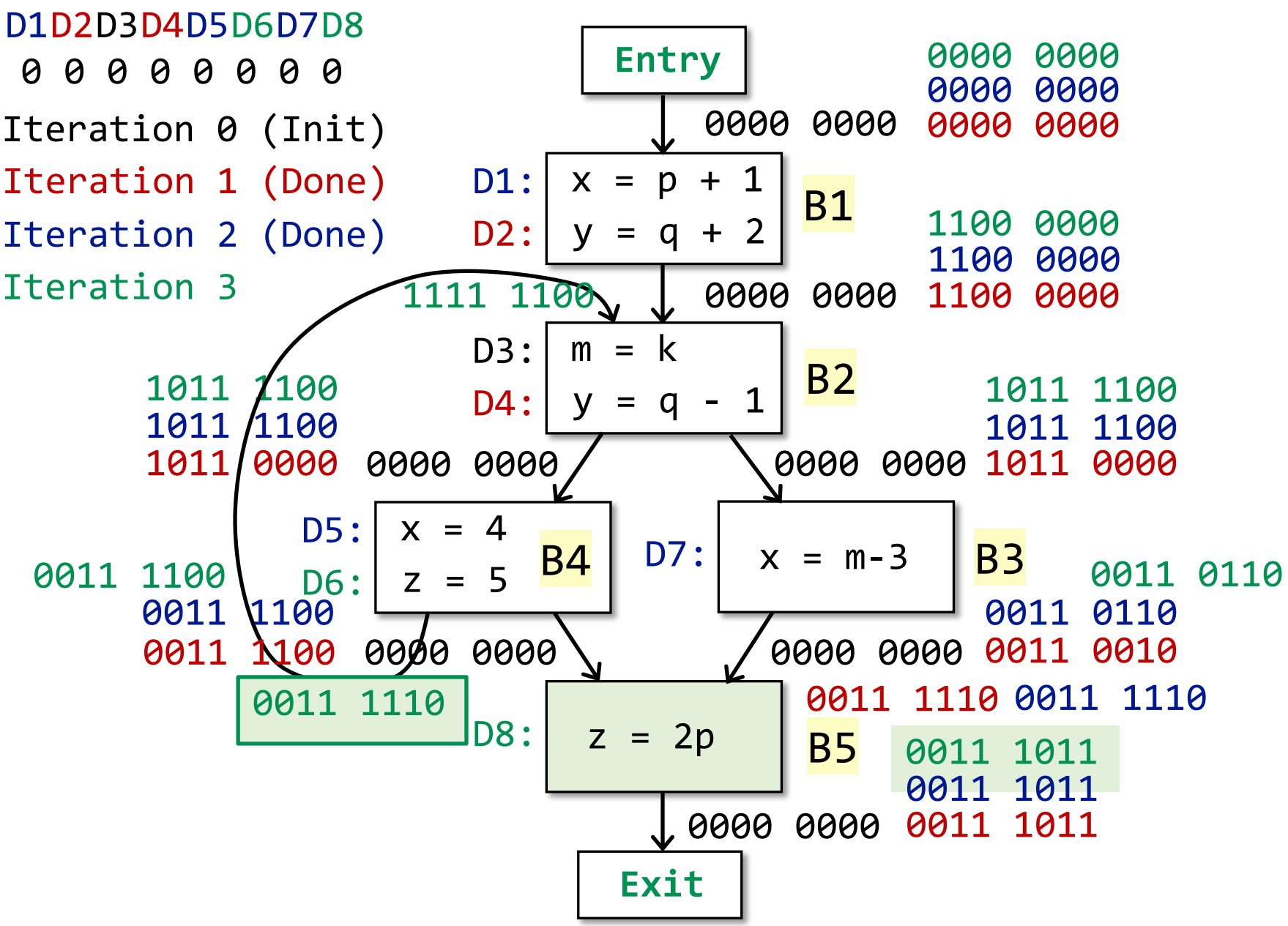

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
D8:
z = 2p
B5
0011 1110 0011 1110
0011 1011
0011 1011
0000 0000
Exit

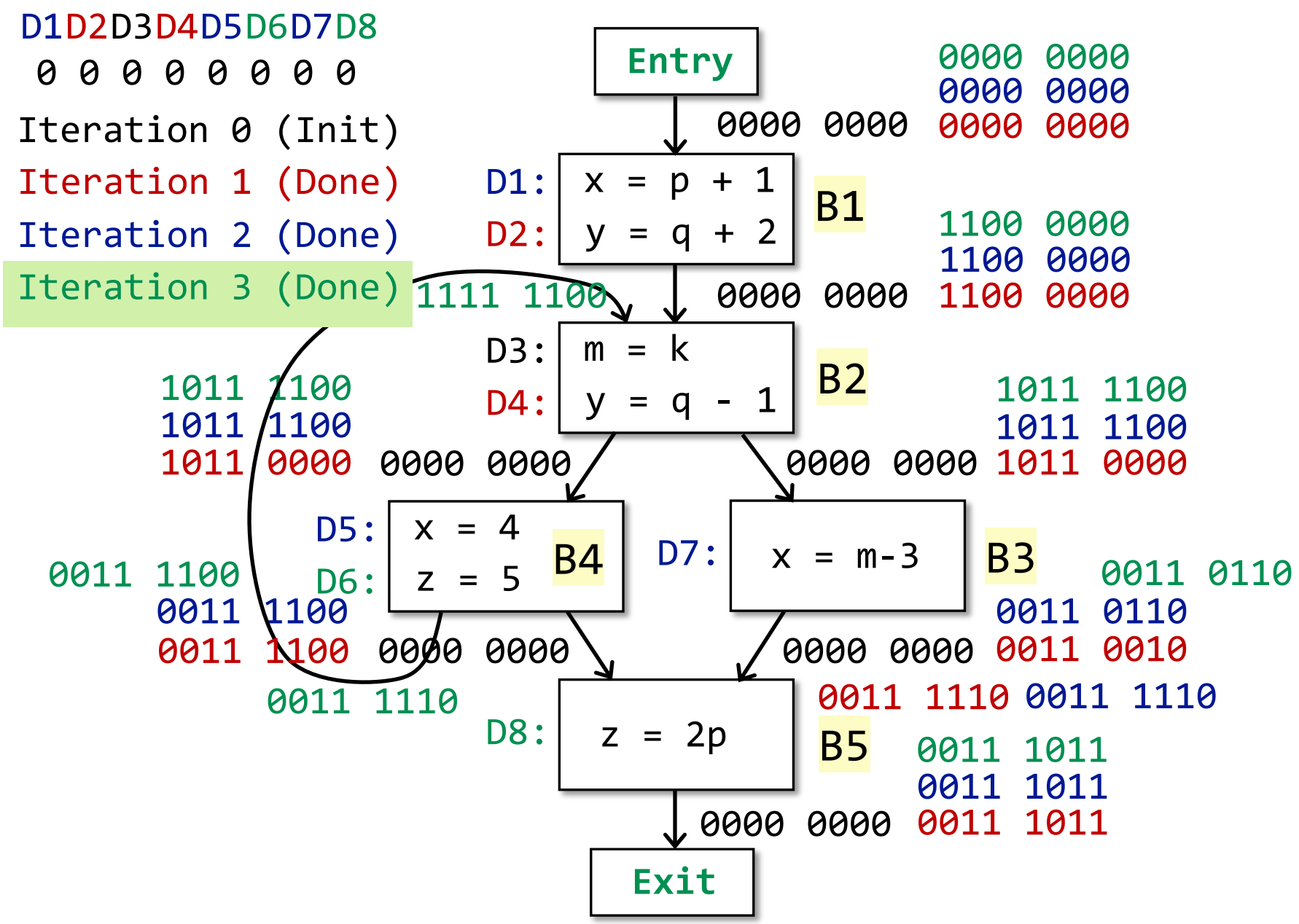

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0000 0000
Exit

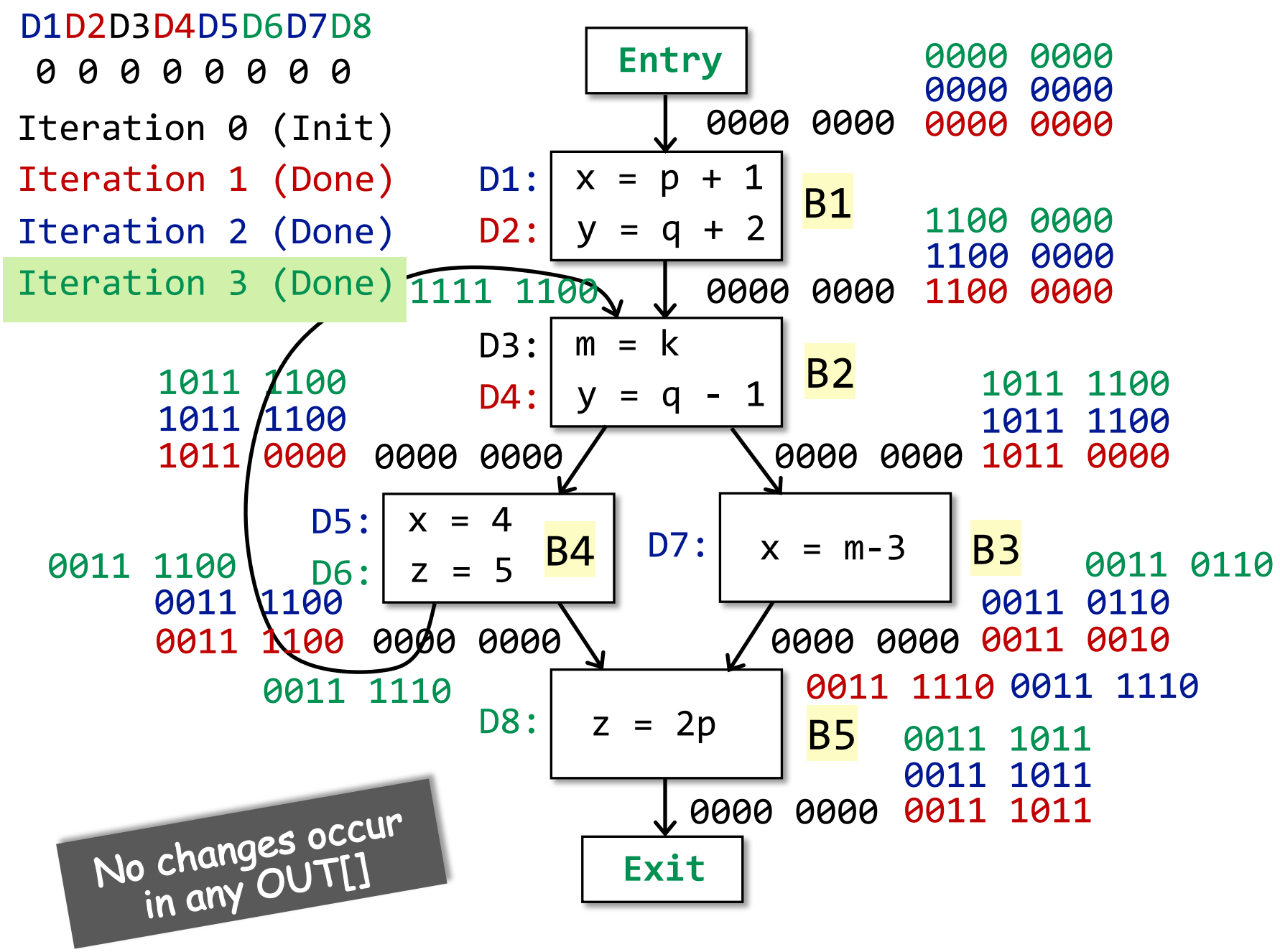

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
U
0011 1110 0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0000 0000
Exit

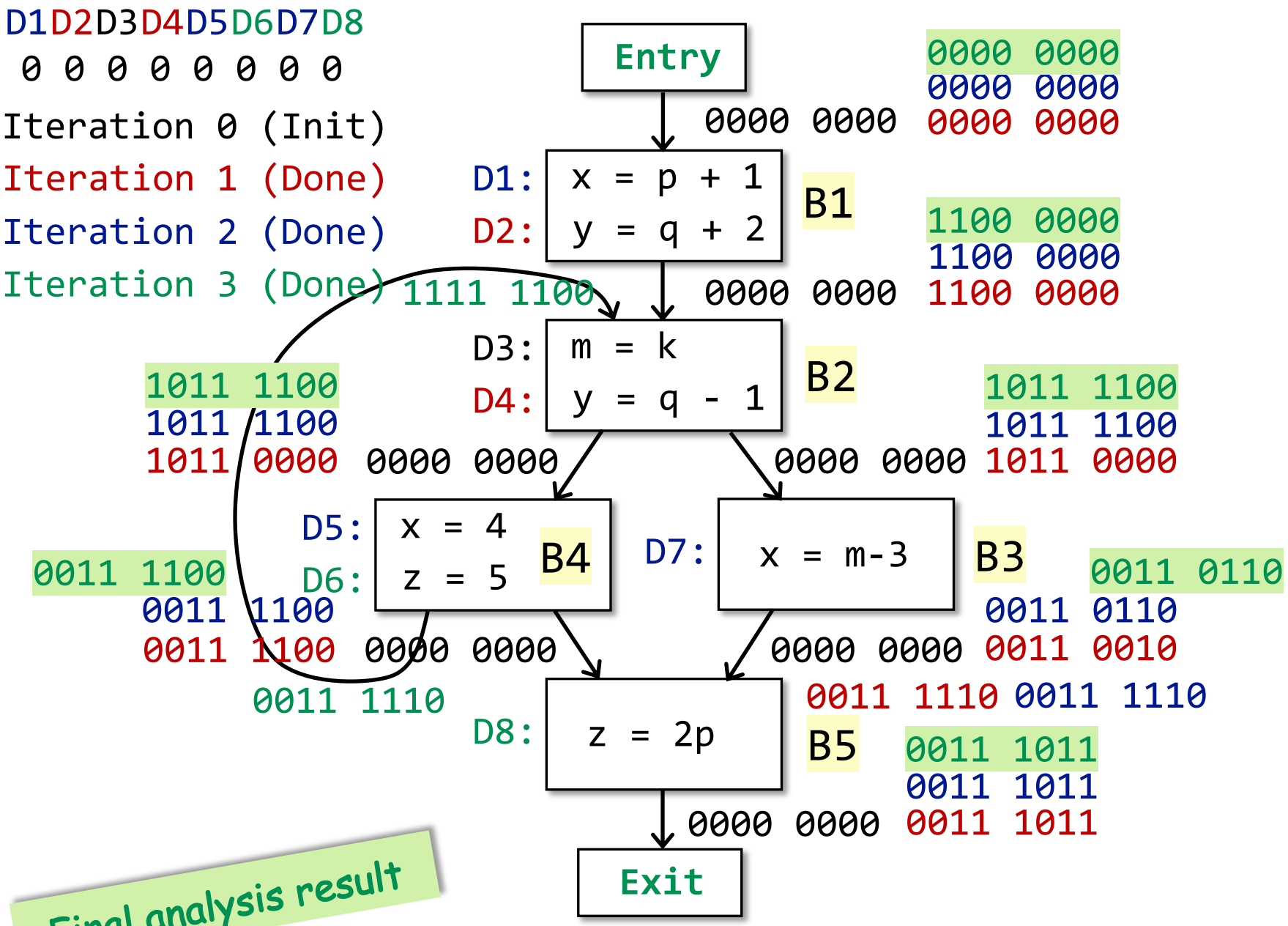

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
z = 5
B4
D6:
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
U
0011 1110
0011 1110
0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0000 0000
Exit


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
z = 5
B4
D6:
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
0011 1110
0011 1110
0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0000 0000
Exit

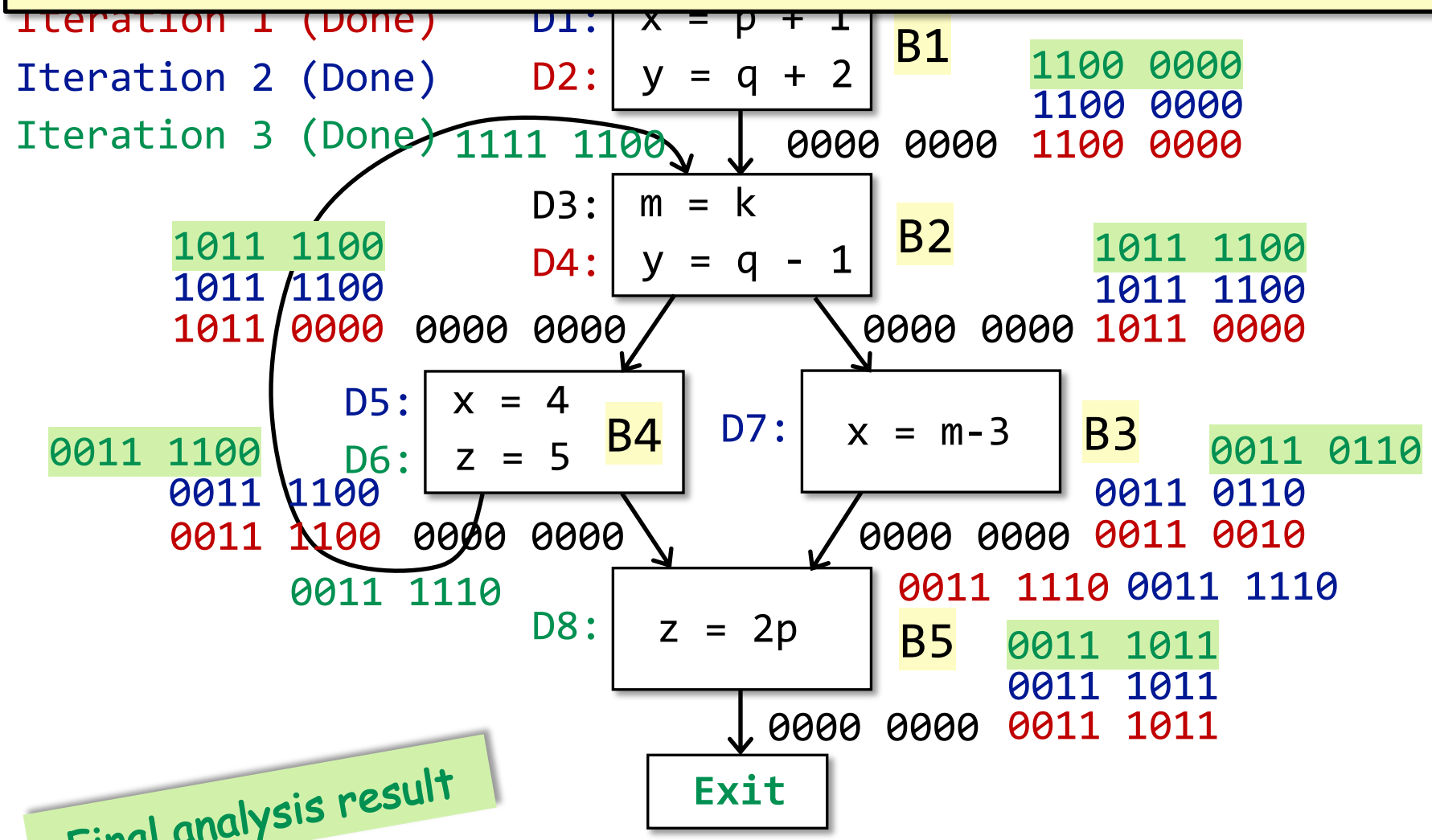

D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 1
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
z = 5
B4
D6:
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
0011 1110
D8:
z = 2p
0011 1110 0011 1110
B5
0011 1011
0011 1011
0011 1011
0000 0000
Exit


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3 (Done)
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
0011 1110
0011 1110
0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0011 1011
0000 0000
Exit


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3 (Done)
Entry
0000 0000
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1100 0000
1100 0000
1111 1100
0000 0000
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
0011 1110
0011 1110
0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0011 1011
0000 0000
0000 0000
Exit
No changes occur in any OUT[]


D1D2D3D4D5D6D7D8
0 0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3 (Done)
Entry
0000 0000
0000 0000
0000 0000
D1:
x = p + 1
D2:
y = q + 2
B1
1100 0000
1100 0000
1100 0000
0000 0000
1111 1100
D3:
m = k
D4:
y = q - 1
B2
1011 1100
1011 1100
1011 0000
1011 1100
1011 1100
1011 0000
0000 0000
0000 0000
D5:
x = 4
D6:
z = 5
B4
D7:
x = m-3
B3
0011 1100
0011 1100
0011 1100
0011 0110
0011 0110
0011 0010
0000 0000
0000 0000
0011 1110
0011 1110
0011 1110
D8:
z = 2p
B5
0011 1011
0011 1011
0011 1011
0000 0000
Exit
Final analysis result

In each data-flow analysis application, we associate with every program point a data-flow value that represents an *abstraction* of the set of all possible program states that can be observed for that point.



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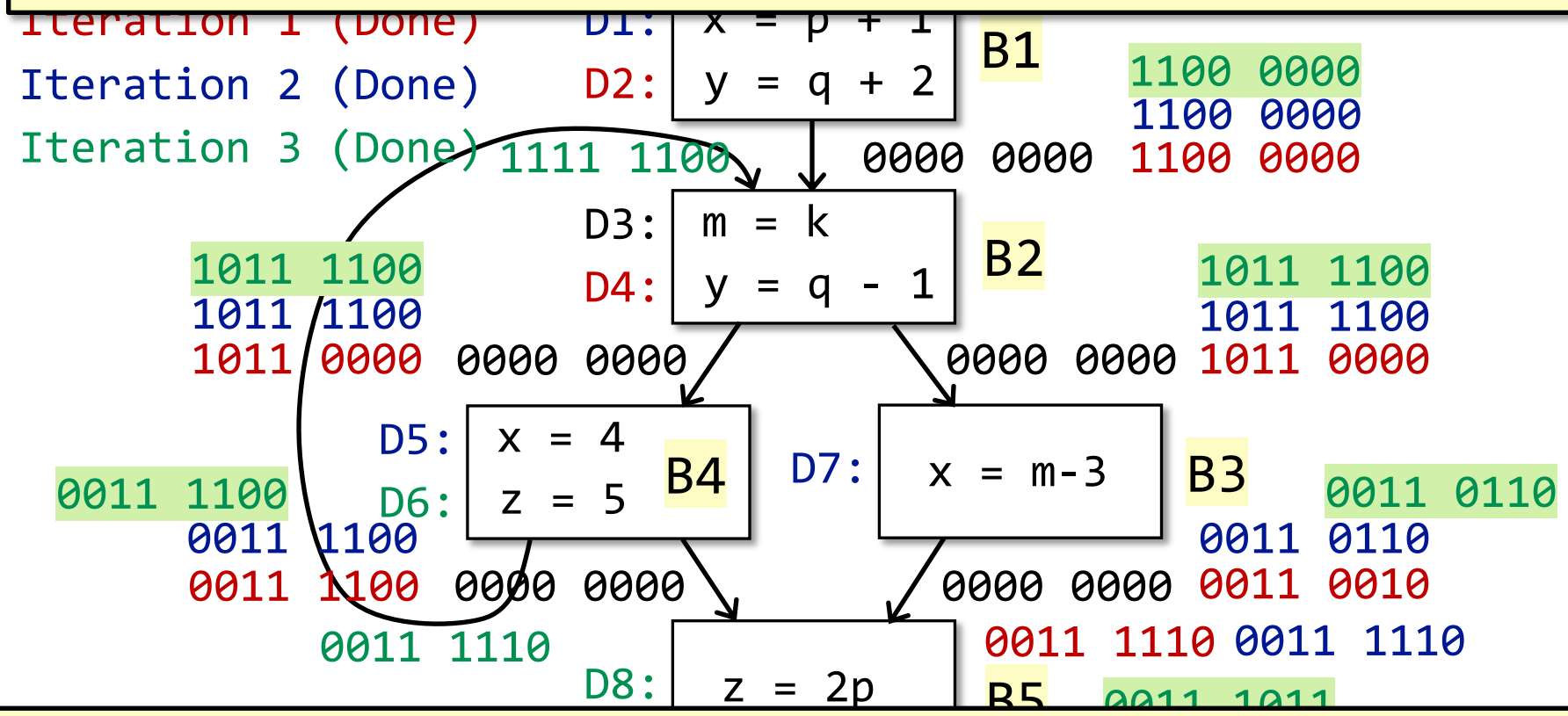

Data-flow analysis is to find a solution to a set of *safe-approximation-directed constraints* on the IN[s]'s and OUT[s]'s, for all statements s.

- *constraints* based on semantics of statements (*transfer functions*)
- *constraints* based on the *flows of control*

Algorithm of Reaching Definitions Analysis

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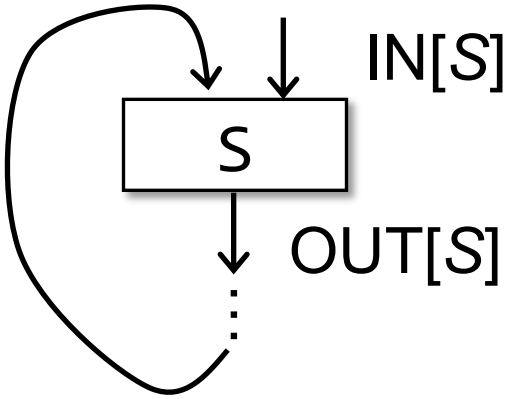
Why this iterative algorithm can finally stop?



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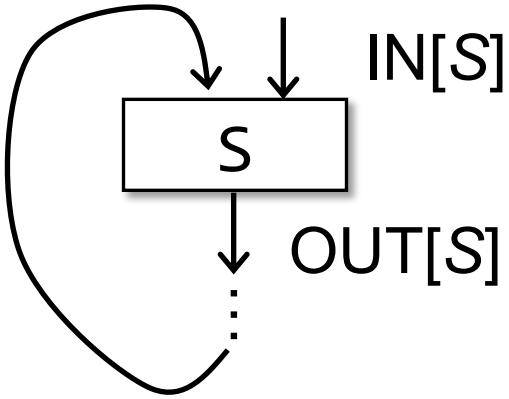

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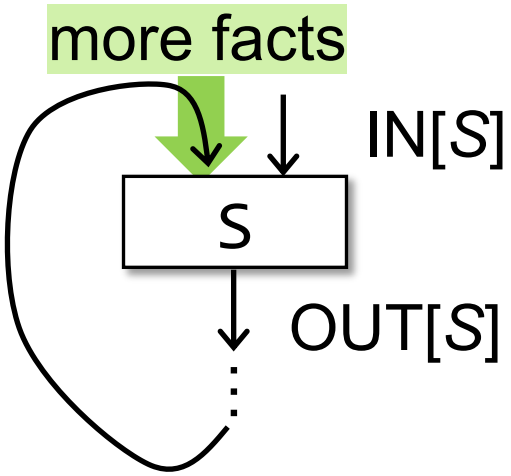

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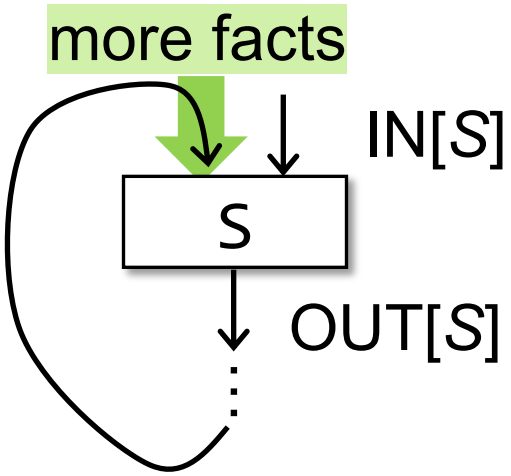

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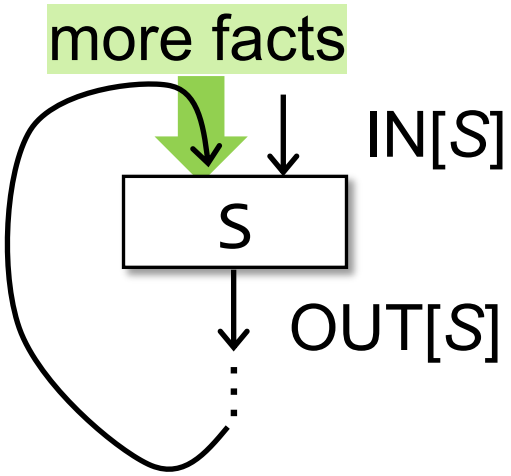

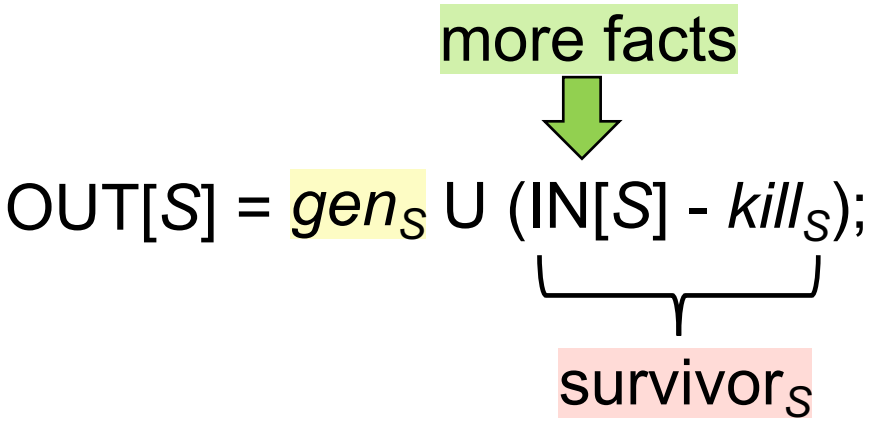

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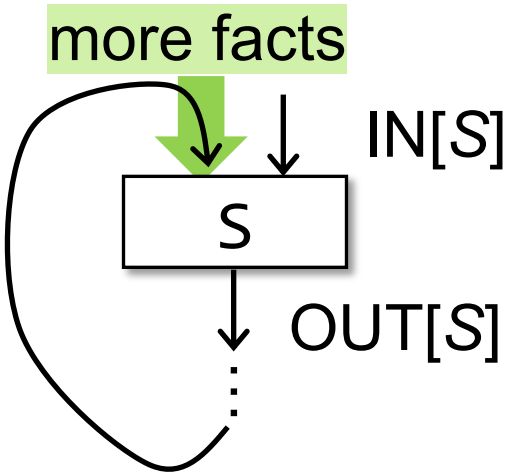

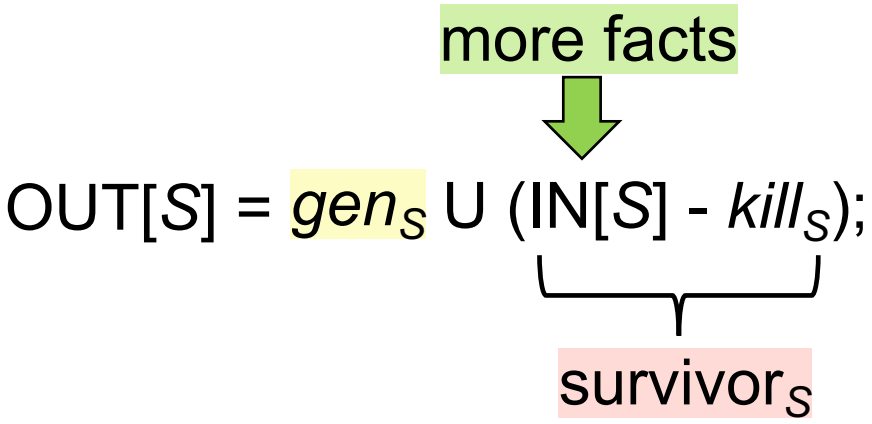

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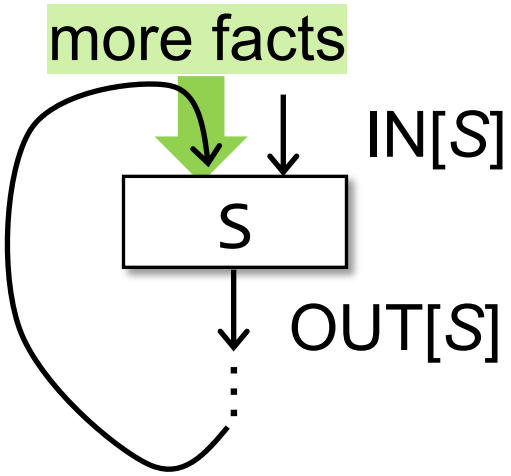

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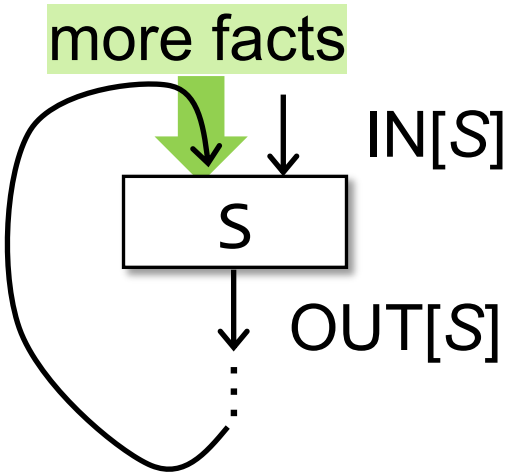

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Reach a fixed point
Also related with monotonicity (next lectures)

Data Flow Analysis Applications

(I) Reaching Definitions Analysis

(II) Live Variables Analysis

(III) Available Expressions Analysis

Live Variables Analysis

Live variables analysis tells whether the value of variable v at program point p could be used along some path in CFG starting at p. If so, v is live at p; otherwise, v is dead at p.

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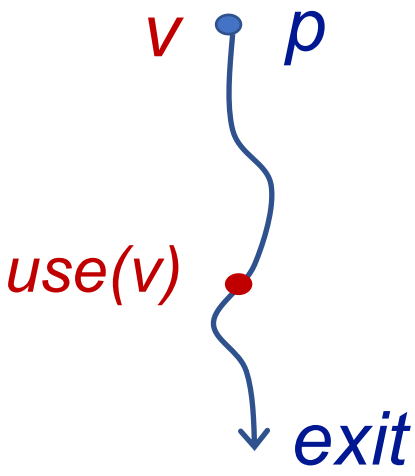

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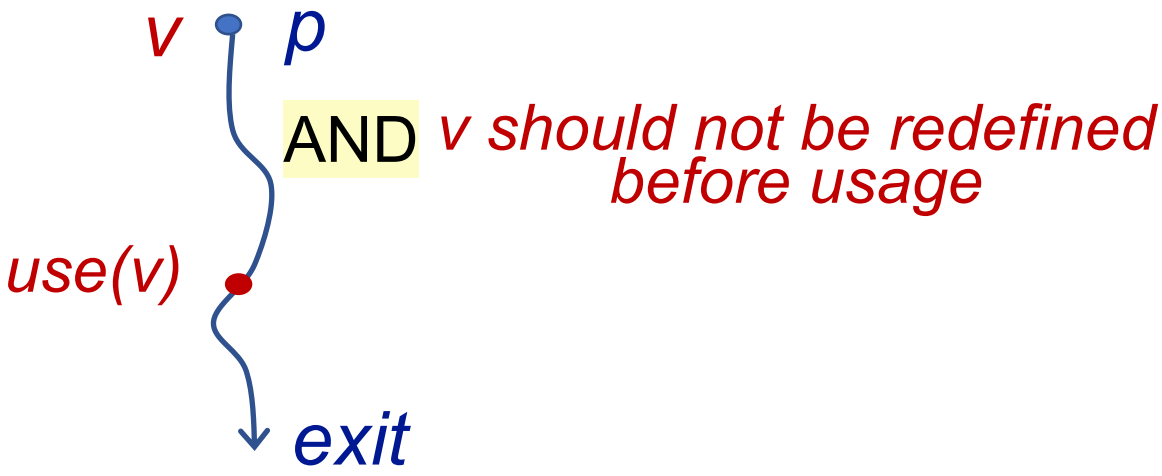

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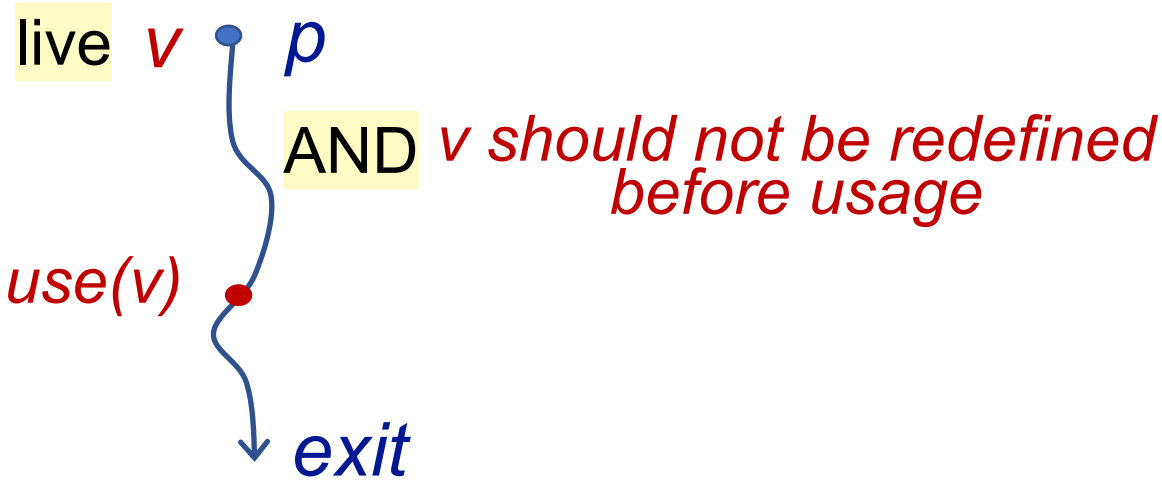

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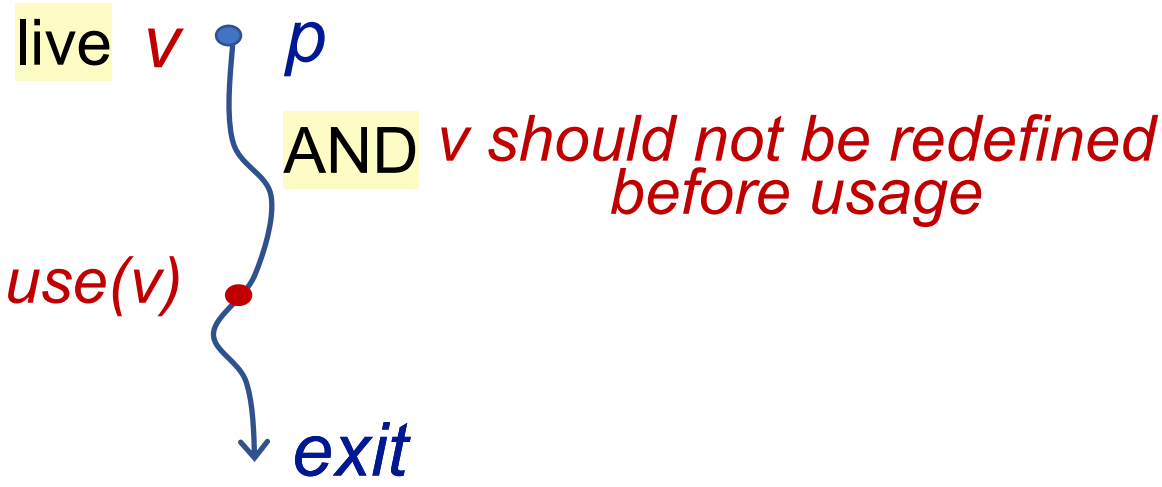
- Information of live variables can be used for register allocations. e.g., at some point all registers are full and we need to use one, then we should favor using a register with a dead value.



Understanding Live Variables Analysis

Abstraction

- Data Flow Values/Facts
  - All the variables in a program
  - Can be represented by bit vectors

e.g., V1, V2, V3, V4, …, V100 (100 variables)

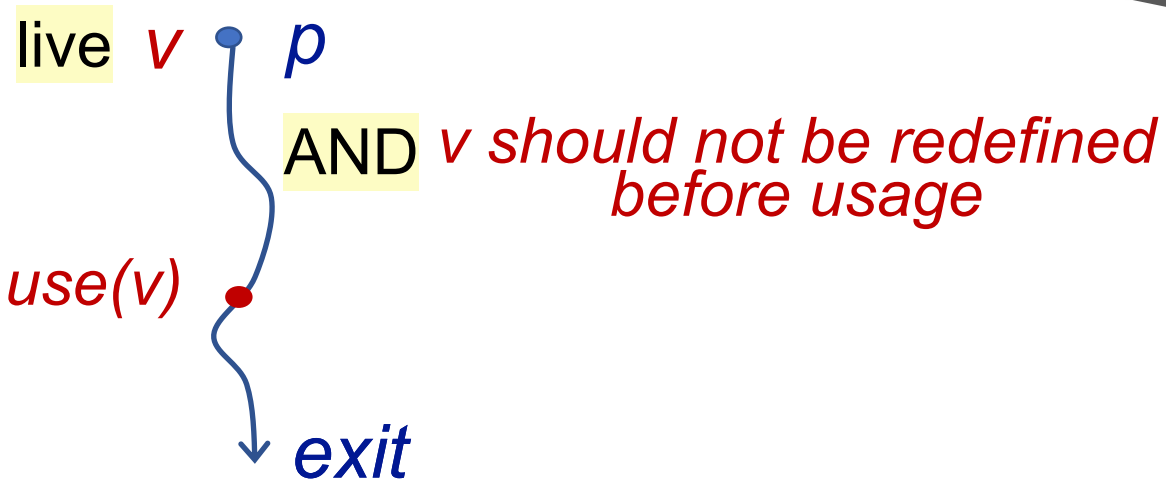
00000…0

100 bits

Bit i from the left represents variable Vi

Understanding Live Variables Analysis

Safe-approximation



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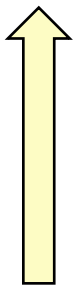

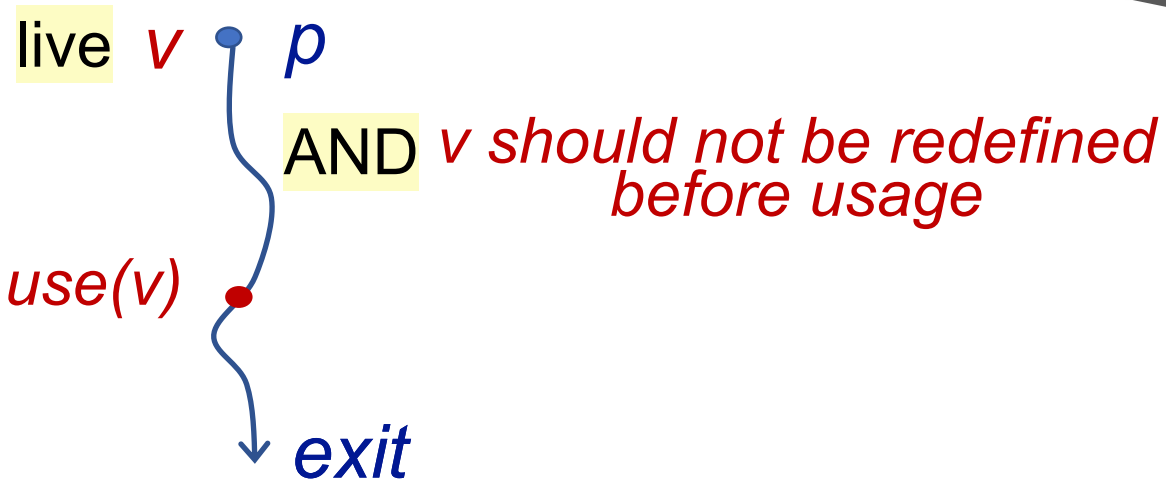

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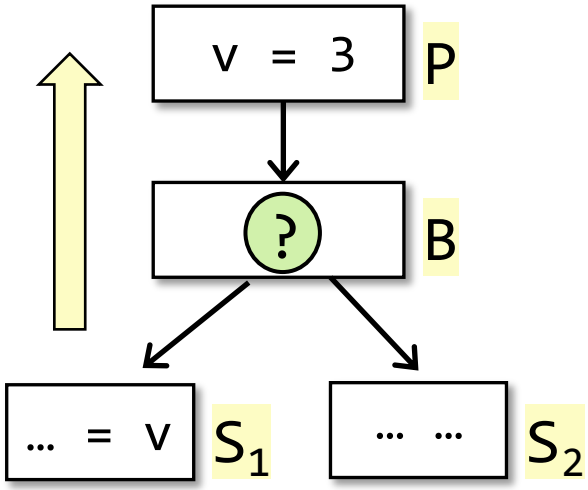

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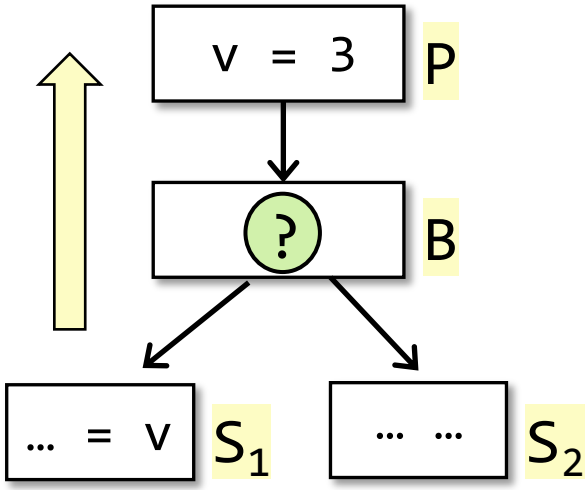

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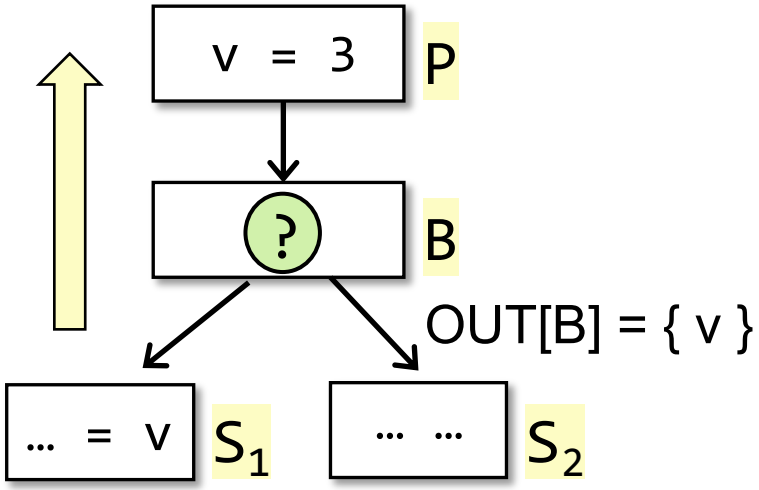
Understanding Live Variables Analysis



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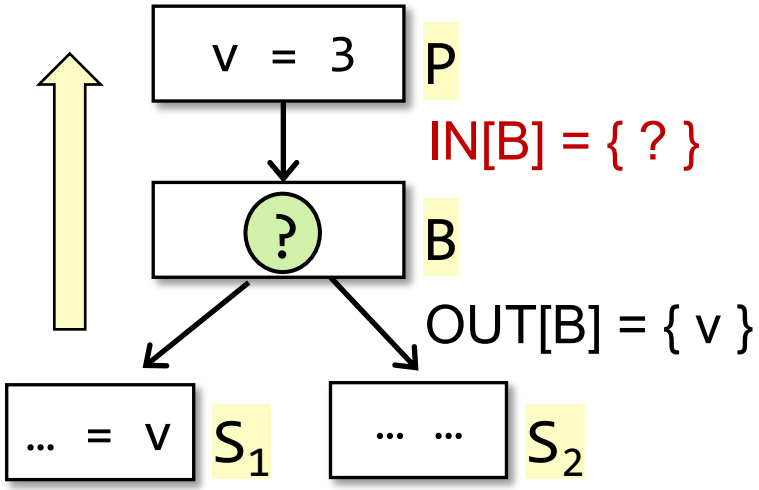

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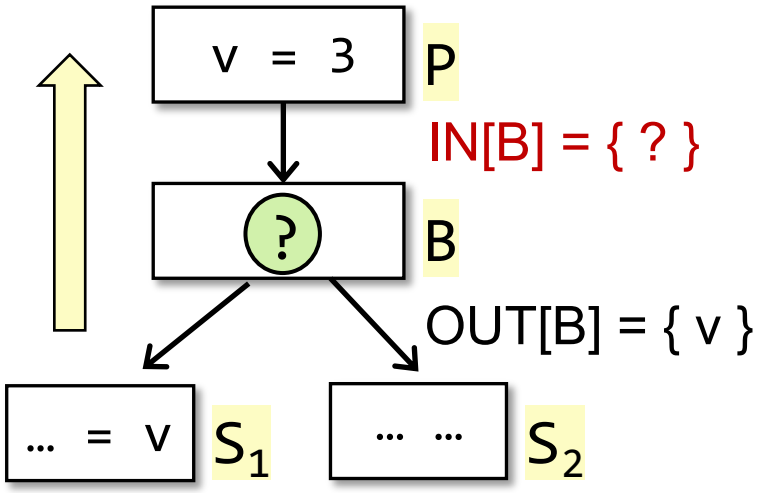

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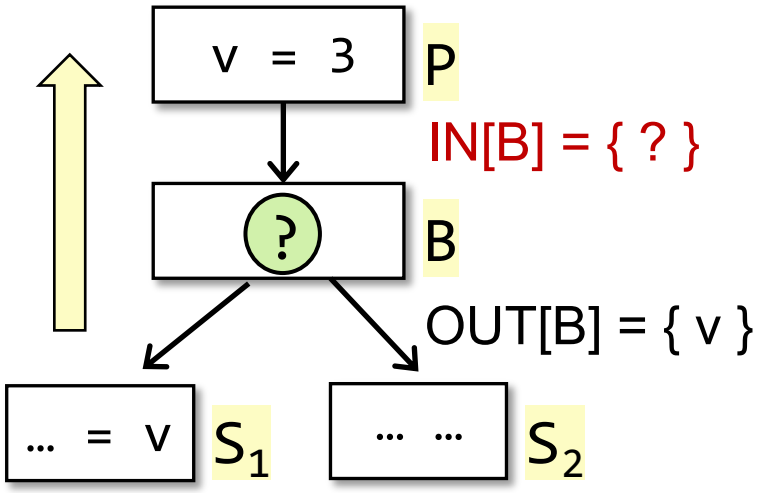

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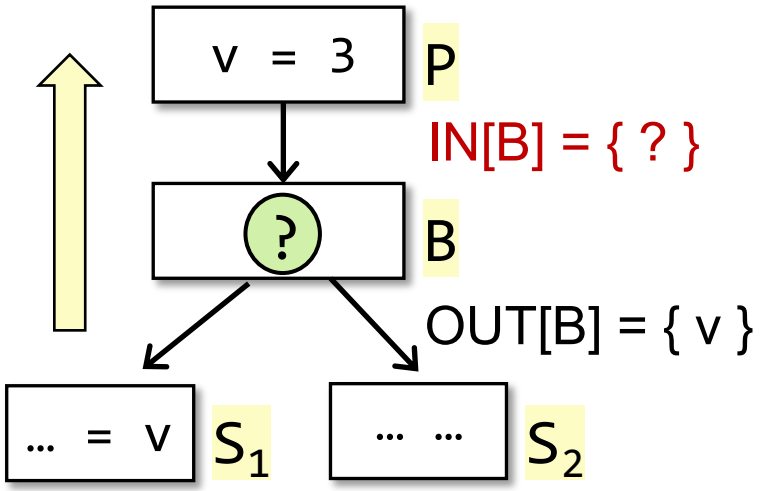

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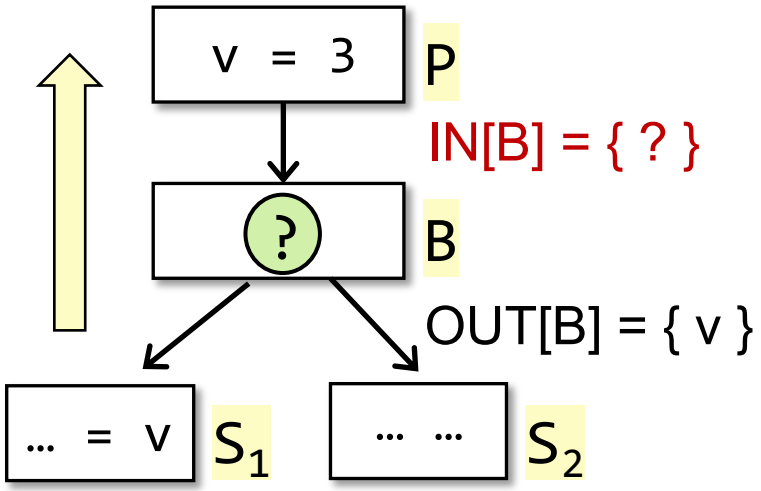

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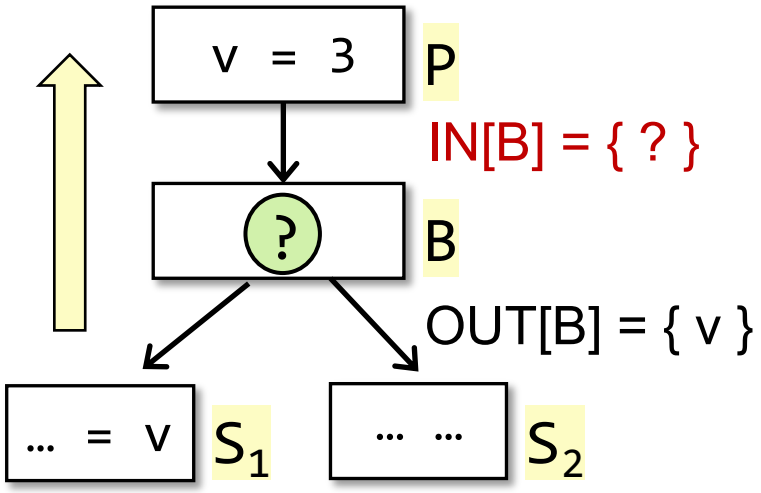

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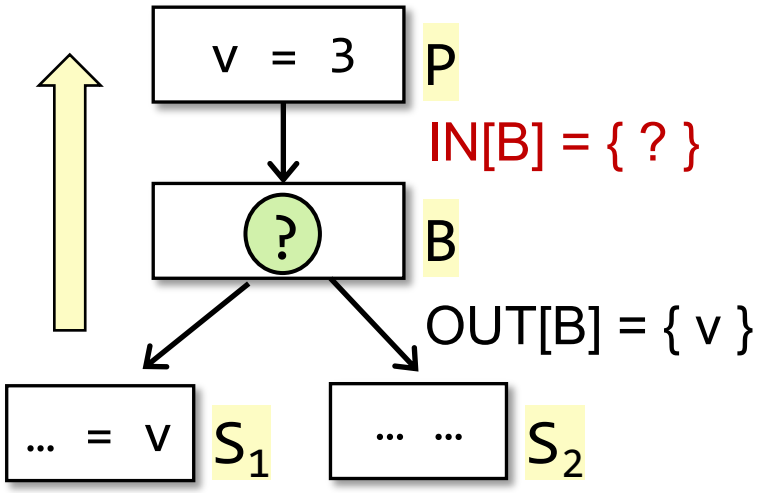

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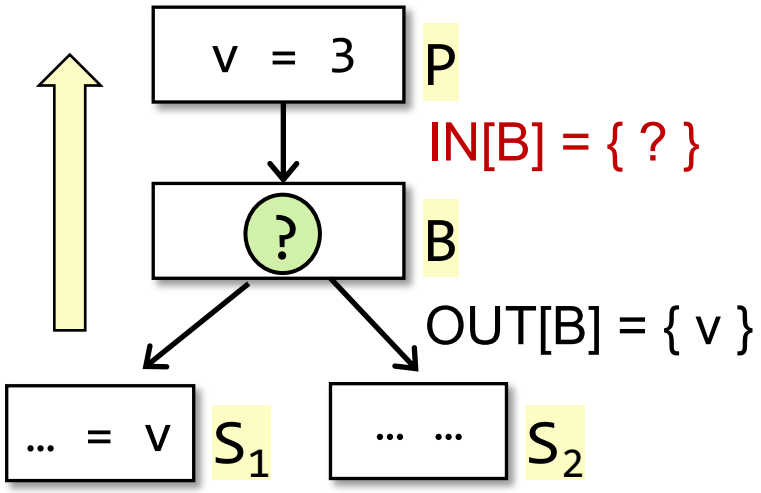

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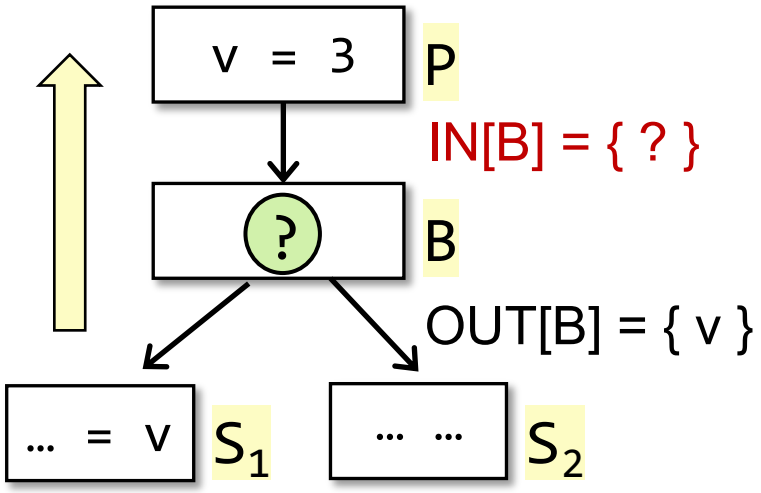
Understanding Live Variables Analysis



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2 k = v

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3 v = 2

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4 v = v-1

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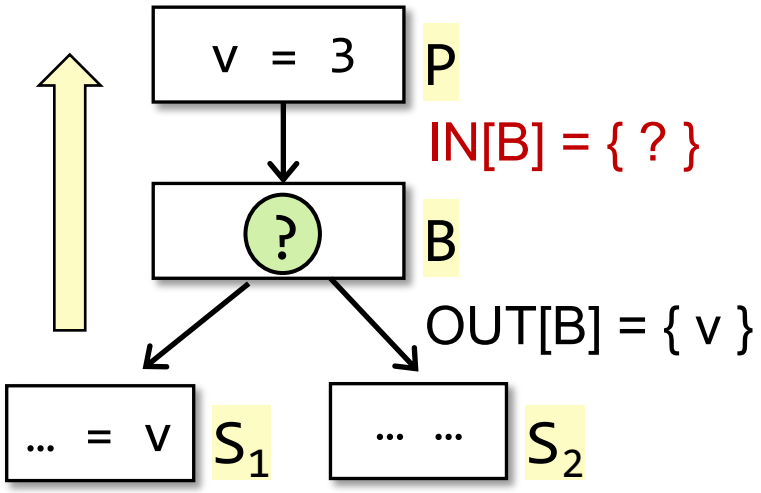

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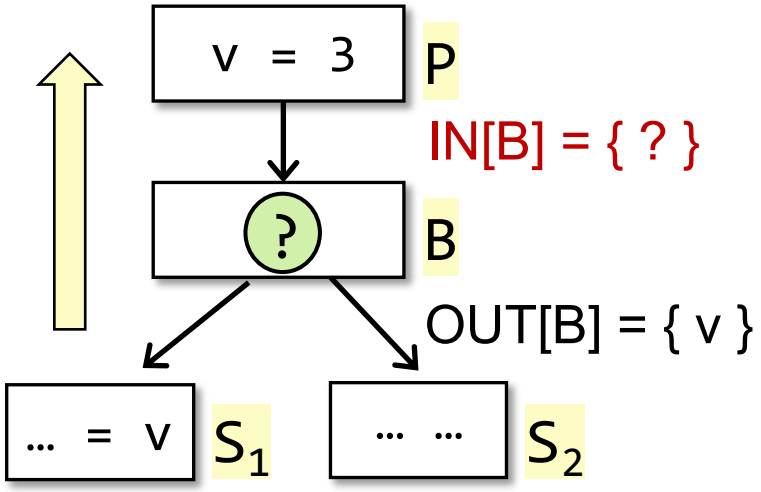

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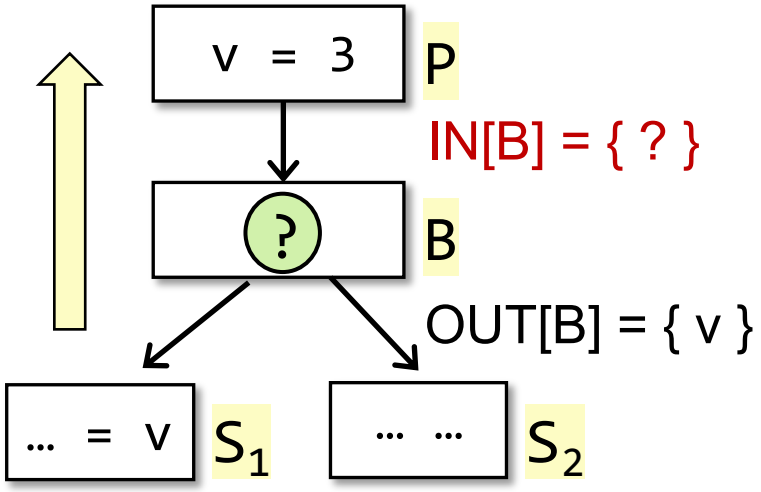
Understanding Live Variables Analysis



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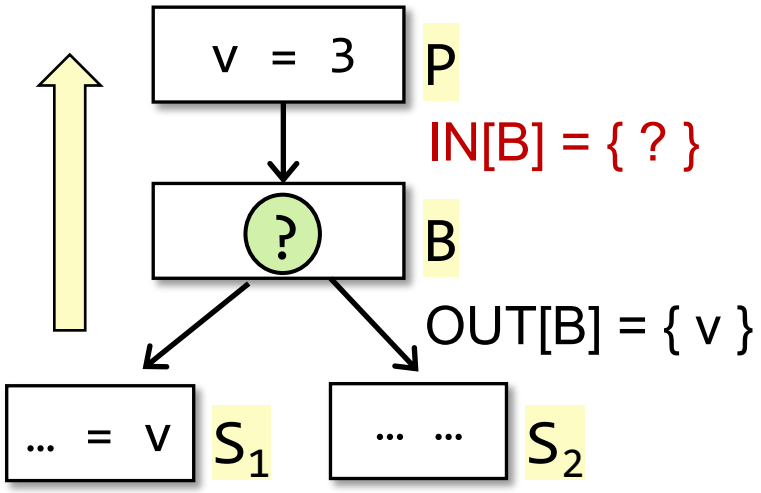

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5. `v = 2`
`k = v` — IN[B] = { }
6. `k = v`
`v = 2`

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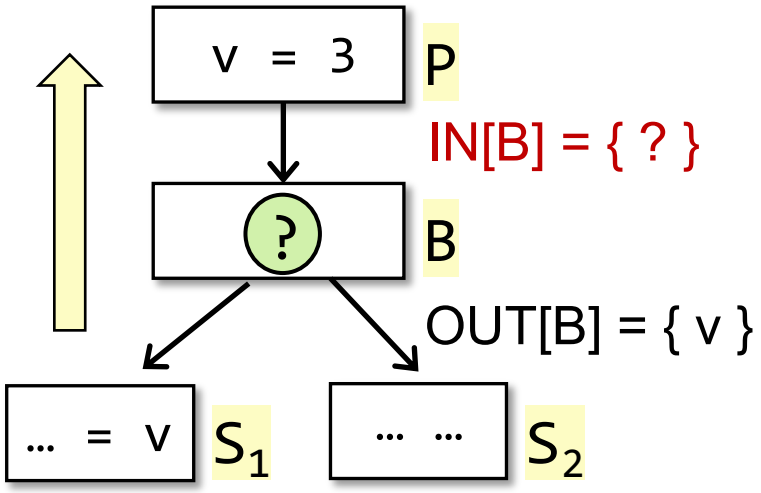
Understanding Live Variables Analysis



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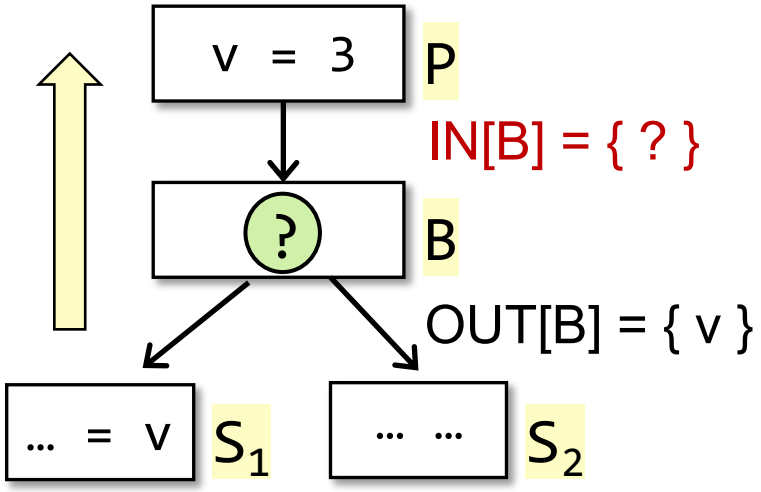

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$$OUT[B] = \bigcup_{S \text{ a successor of } B} IN[S]$$

$$IN[B] = use_B \cup (OUT[B] - def_B)$$

Algorithm of Live Variables Analysis

INPUT: CFG (def_B and use_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

IN[*exit*]= ∅;
for (each basic block $B \backslash exit$)
    IN[B] = ∅;
while (changes to any IN occur)
    for (each basic block $B \backslash exit$) {
        OUT[B] = $\bigcup_{S \text{ a successor of } B}$ IN[S];
        IN[B] = use_B U (OUT[B] - def_B);
    }

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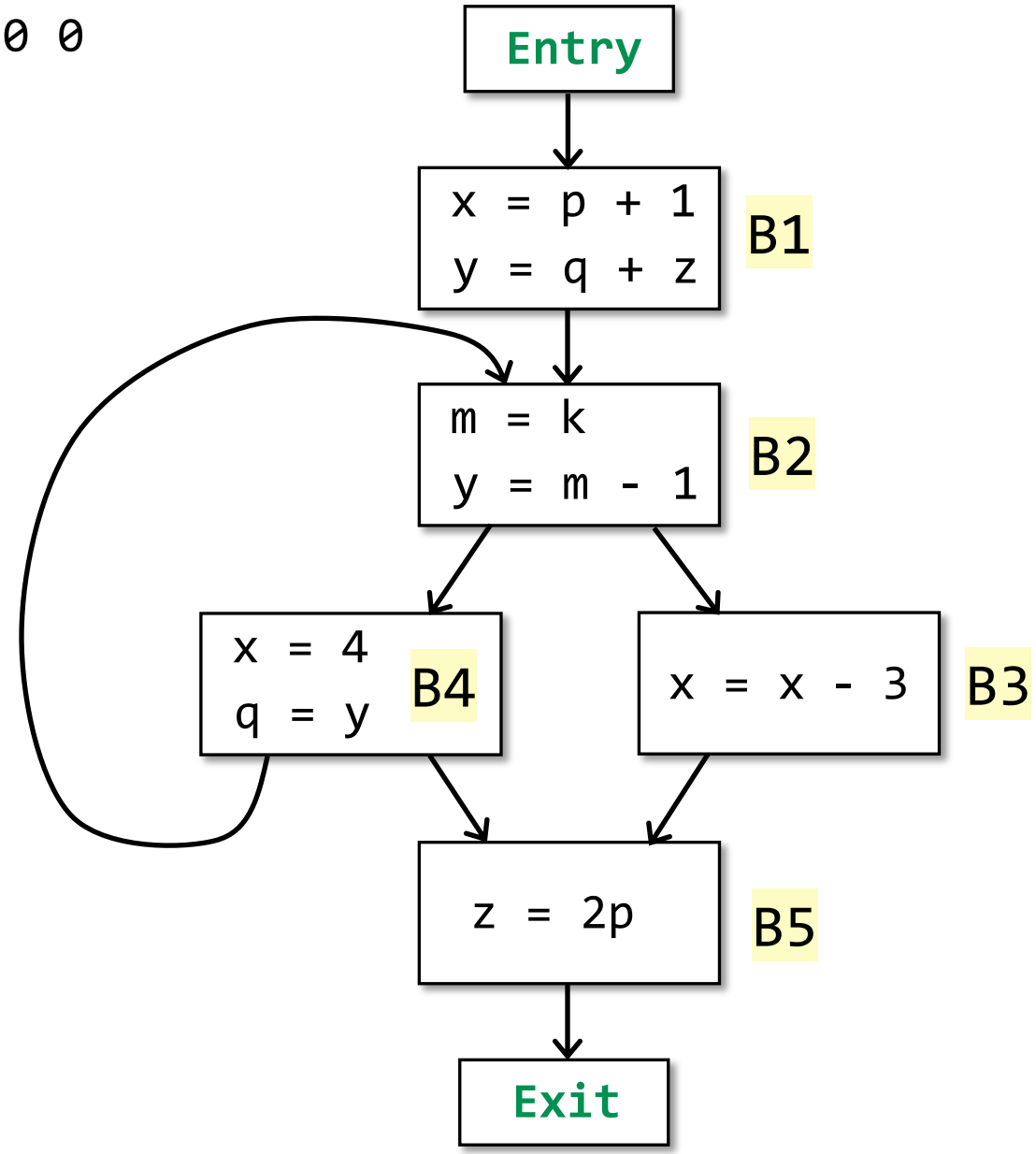
METHOD:

```
IN[exit] = ∅;
for (each basic block B\exit)
    IN[B] = ∅;
 while (changes to any IN occur)
    for (each basic block B\exit) {
        OUT[B] = ⋃ IN[S];   (S a successor of B)
        IN[B] = use_B U (OUT[B] - def_B);
    }
```

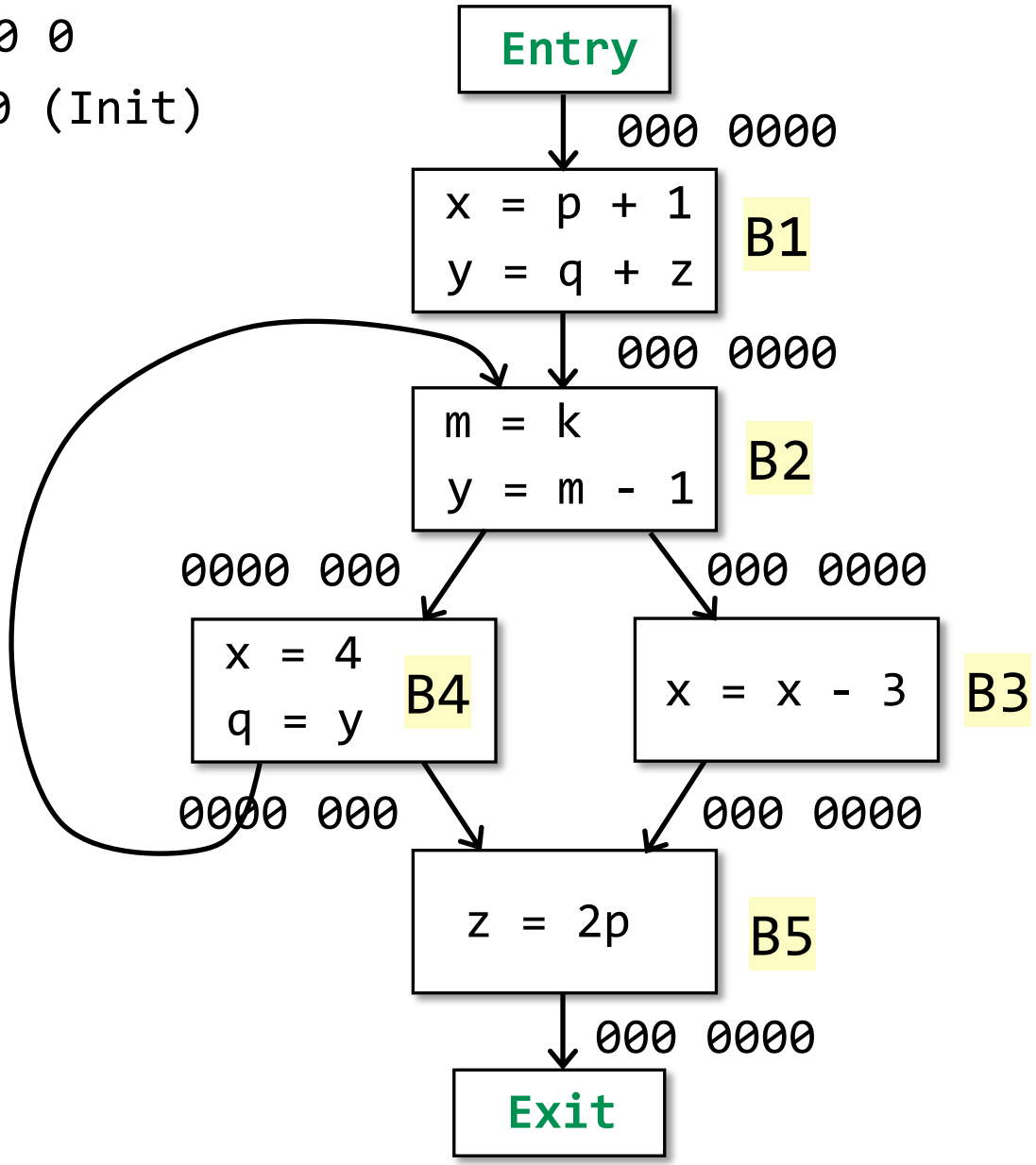
x y z p q m k
0 0 0 0 0 0 0



x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

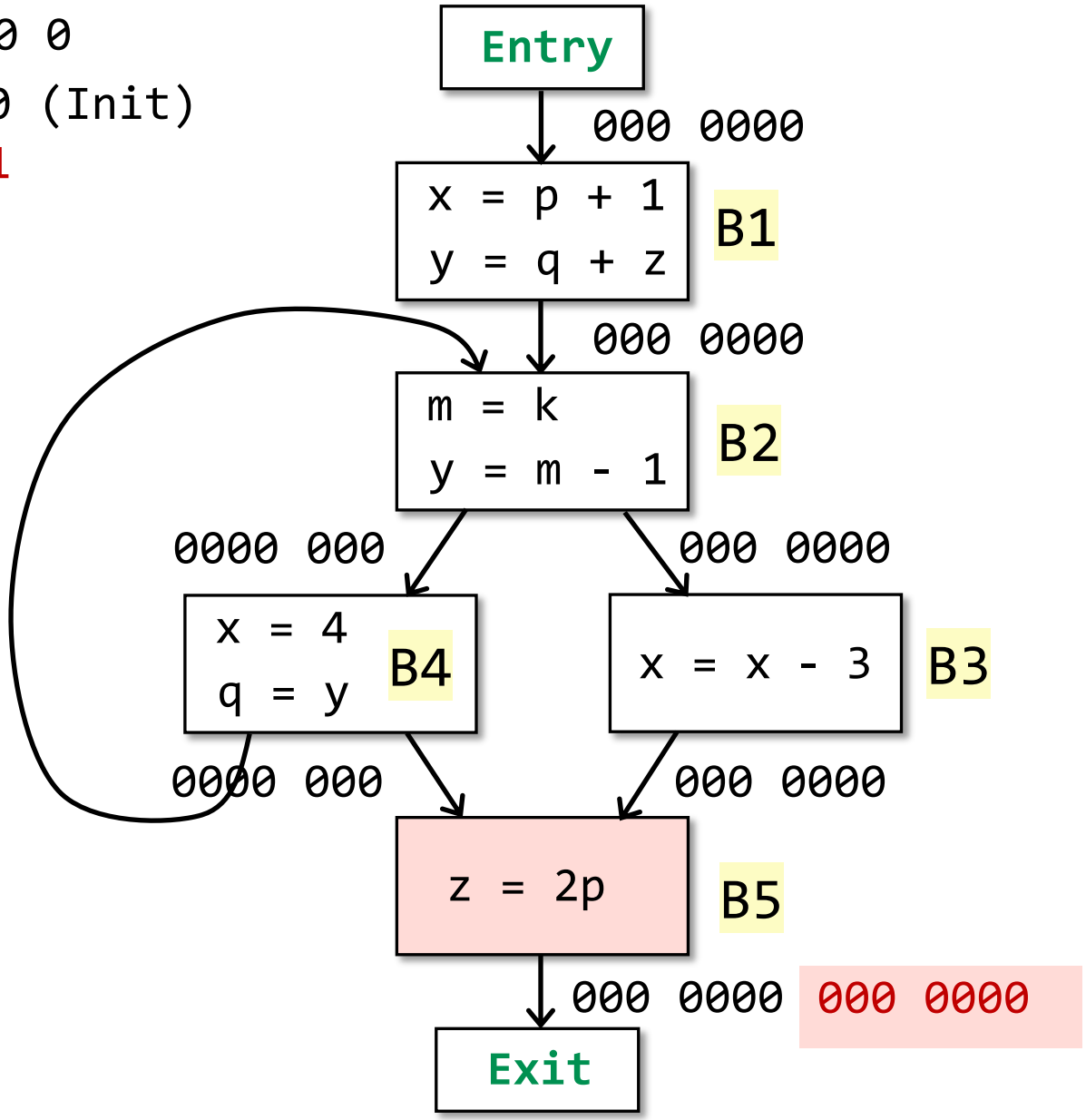


x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1



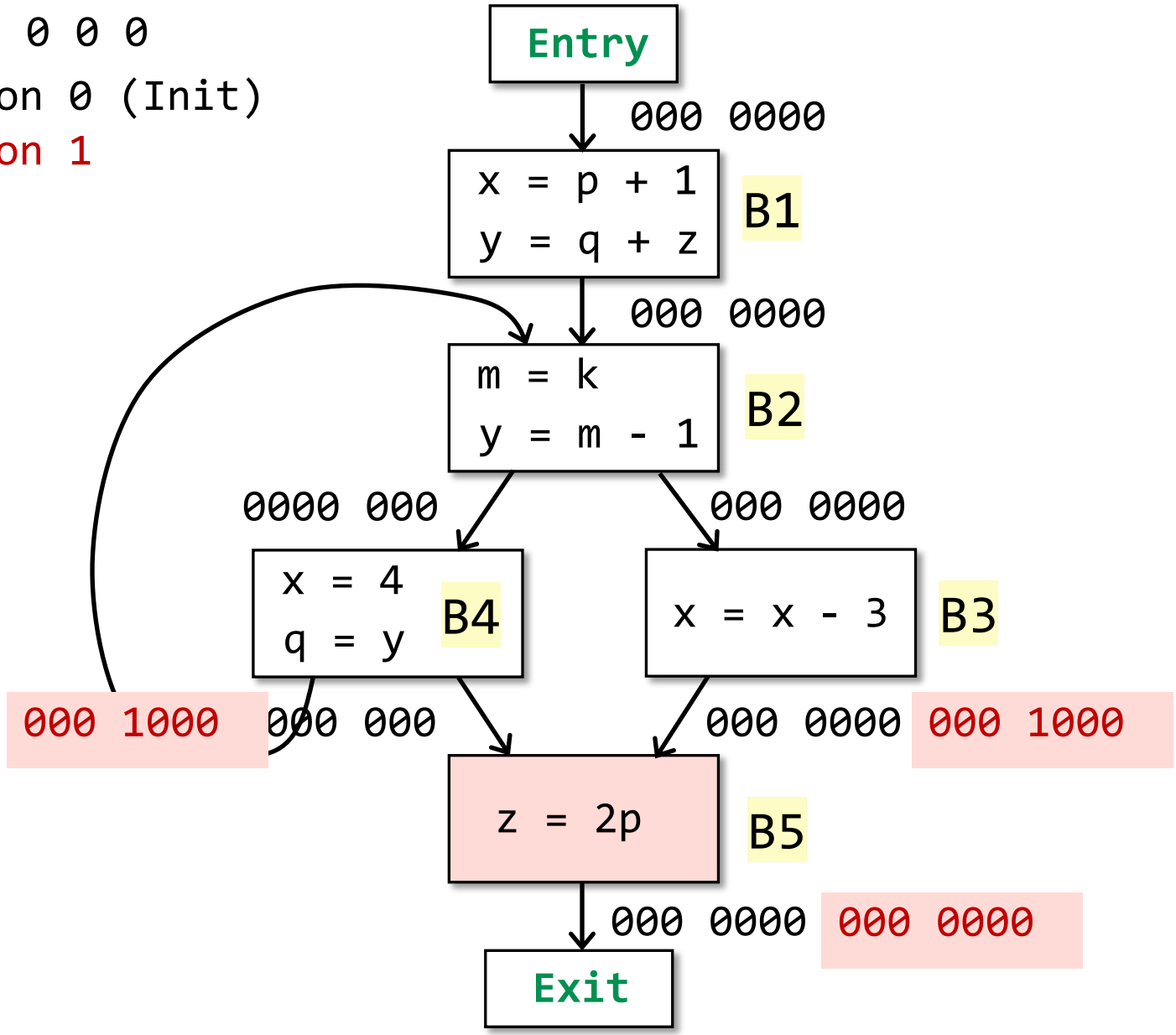
IN[B] = use_B U (OUT[B] - def_B)

x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1



x y z p q m k

0 0 0 0 0 0 0

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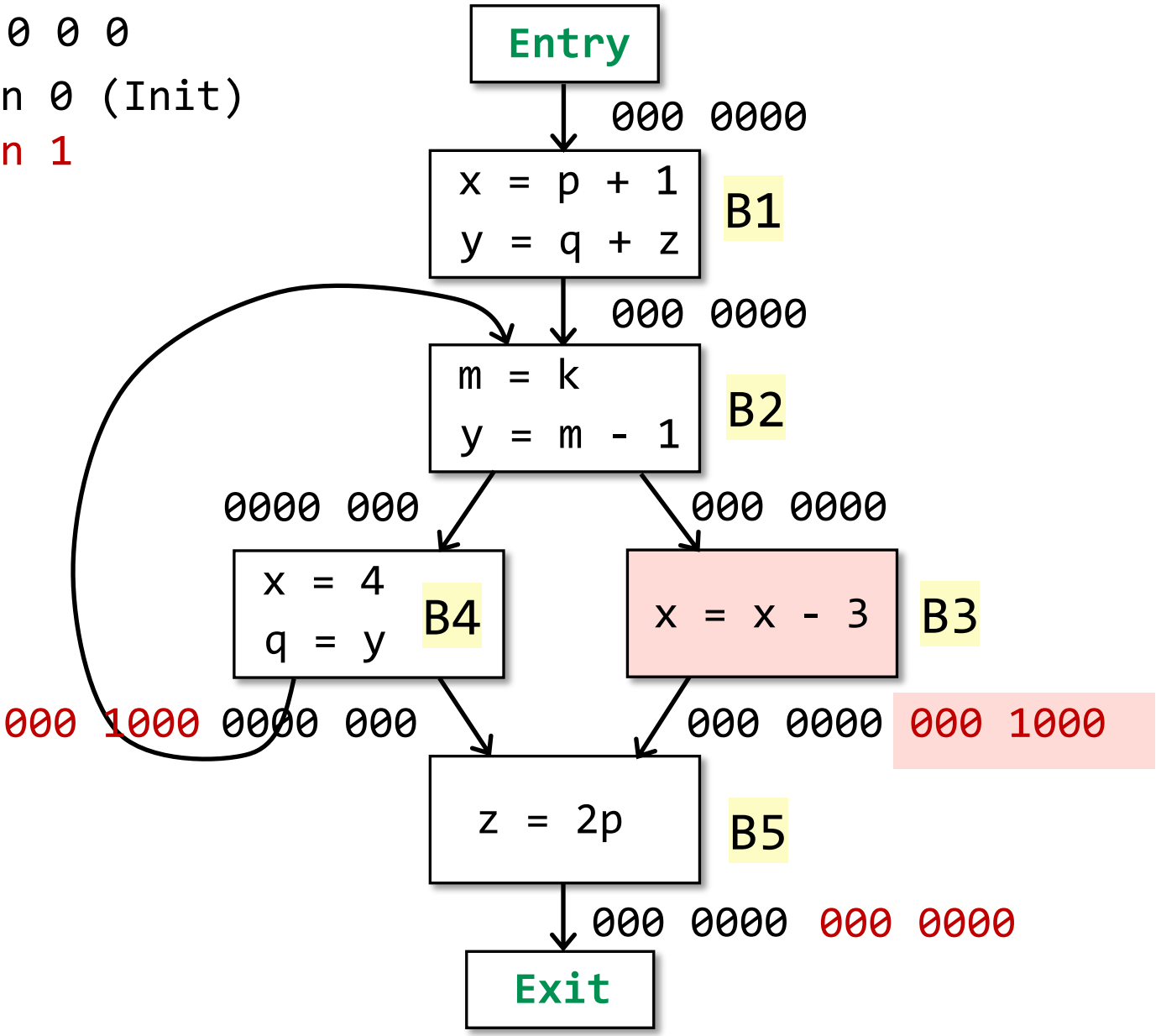
Iteration 1



x y z p q m k

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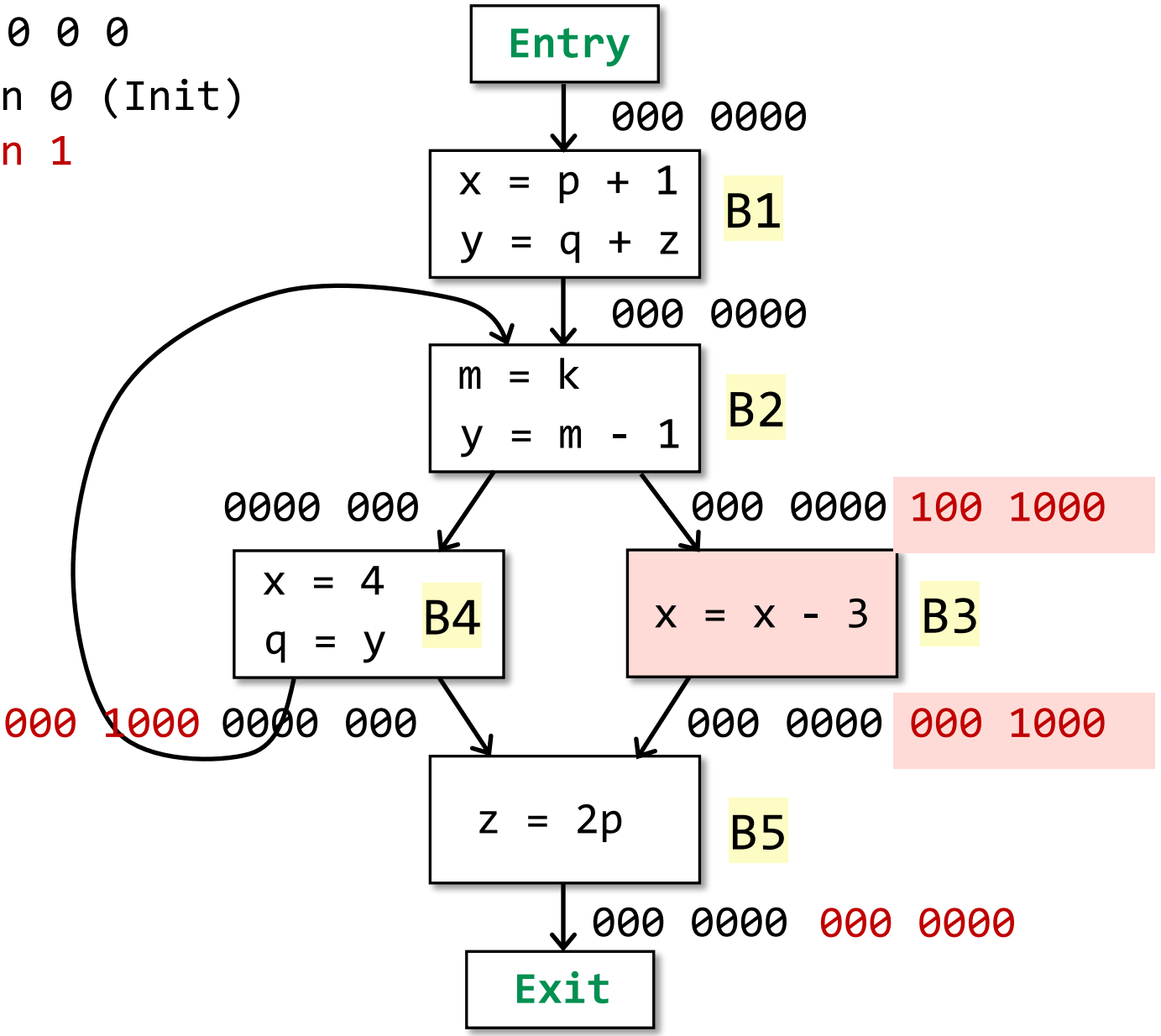
Iteration 1



x y z p q m k

0 0 0 0 0 0 0

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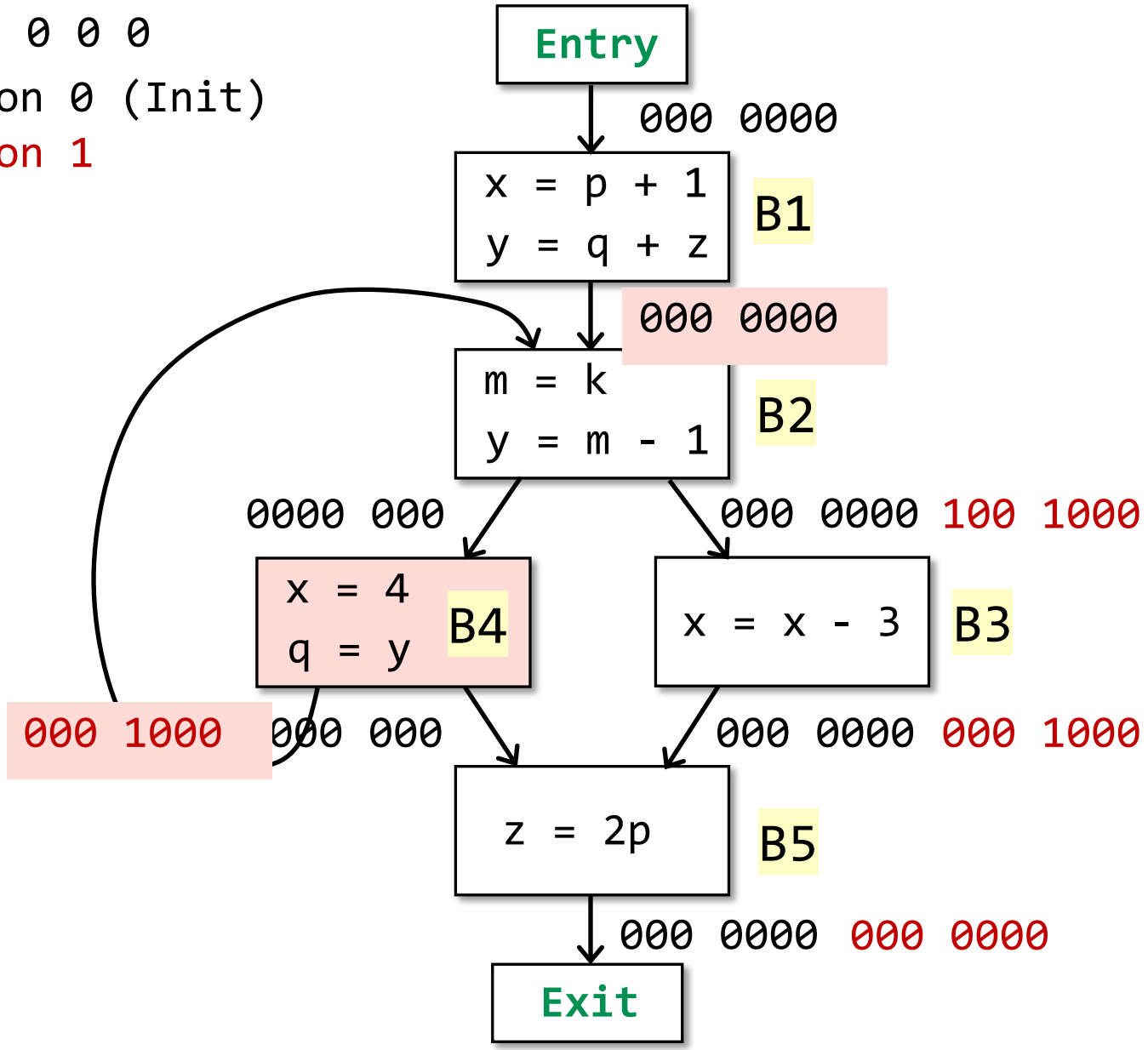
Iteration 1



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0 0 0 0 0 0 0

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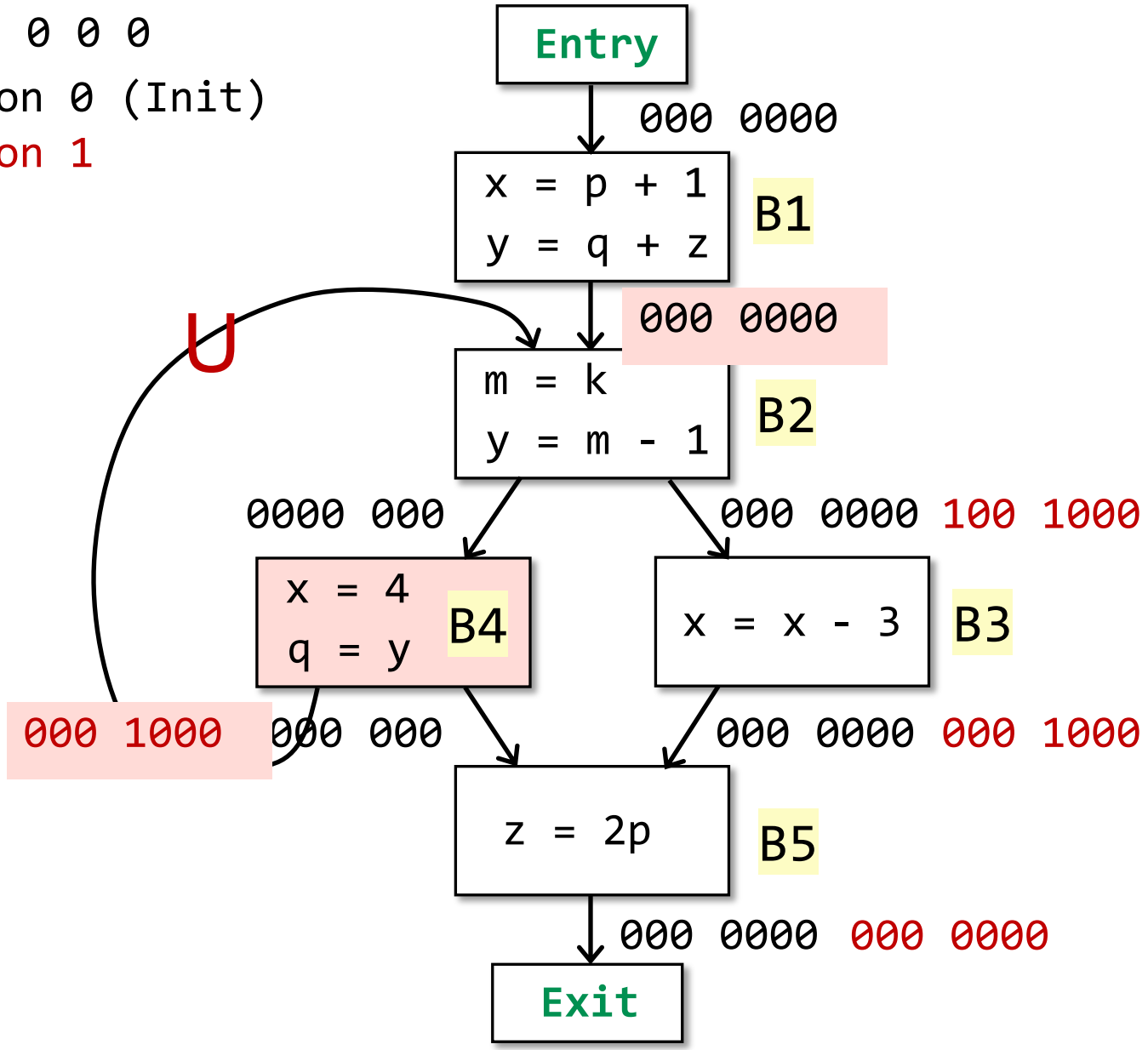

x y z p q m k

0 0 0 0 0 0 0

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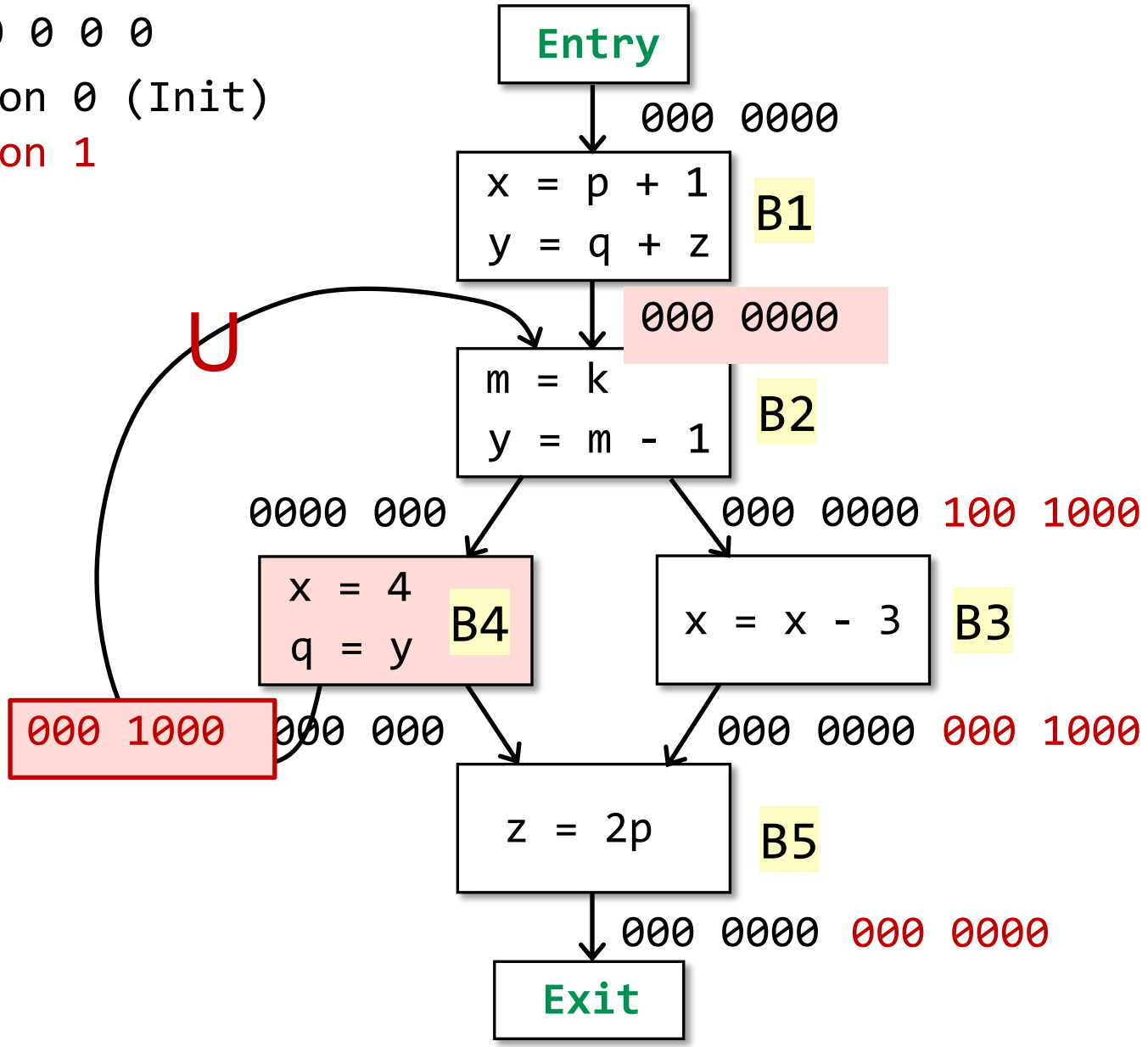
Iteration 1



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0 0 0 0 0 0 0

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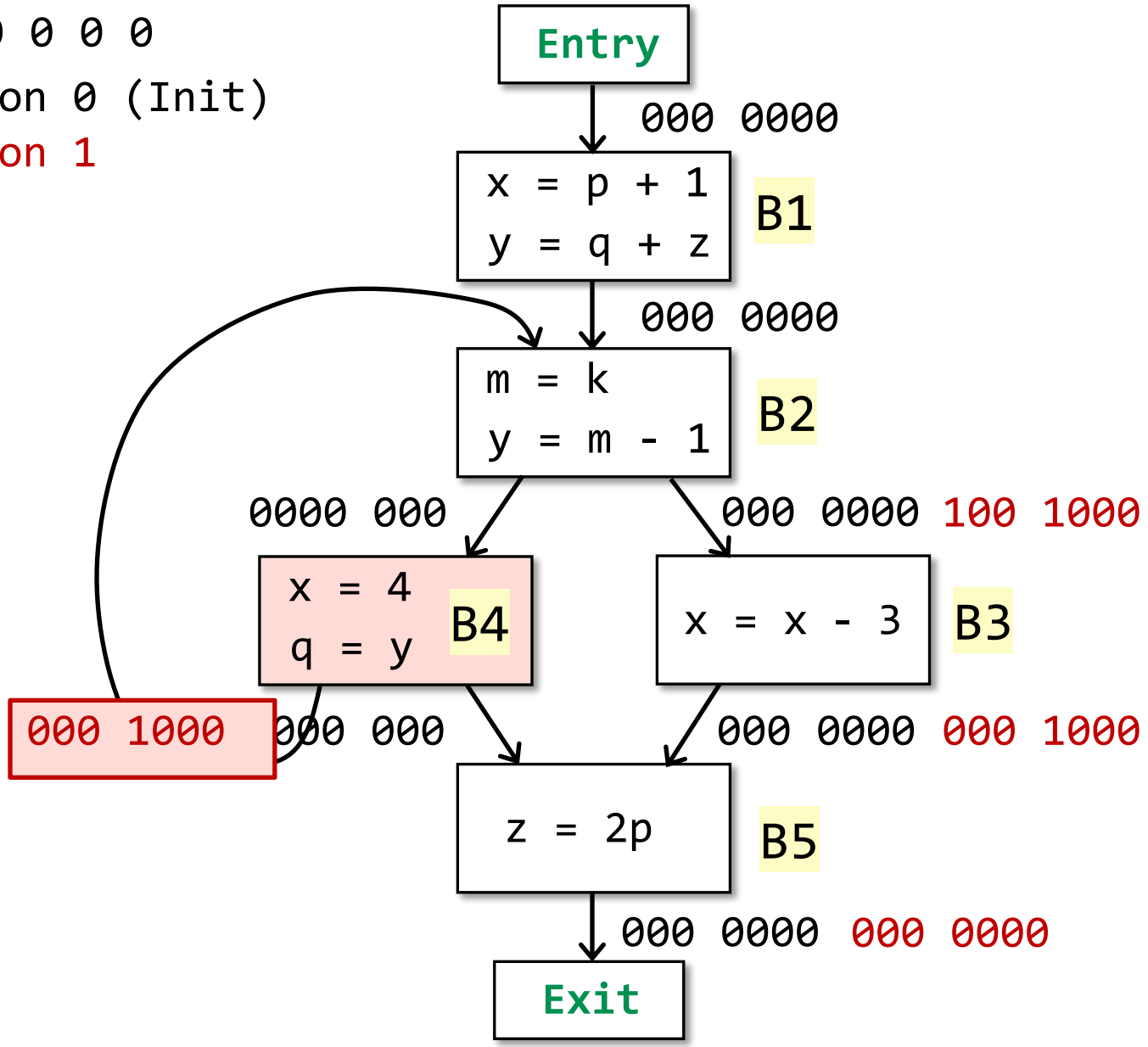
Iteration 1



x y z p q m k

0 0 0 0 0 0 0

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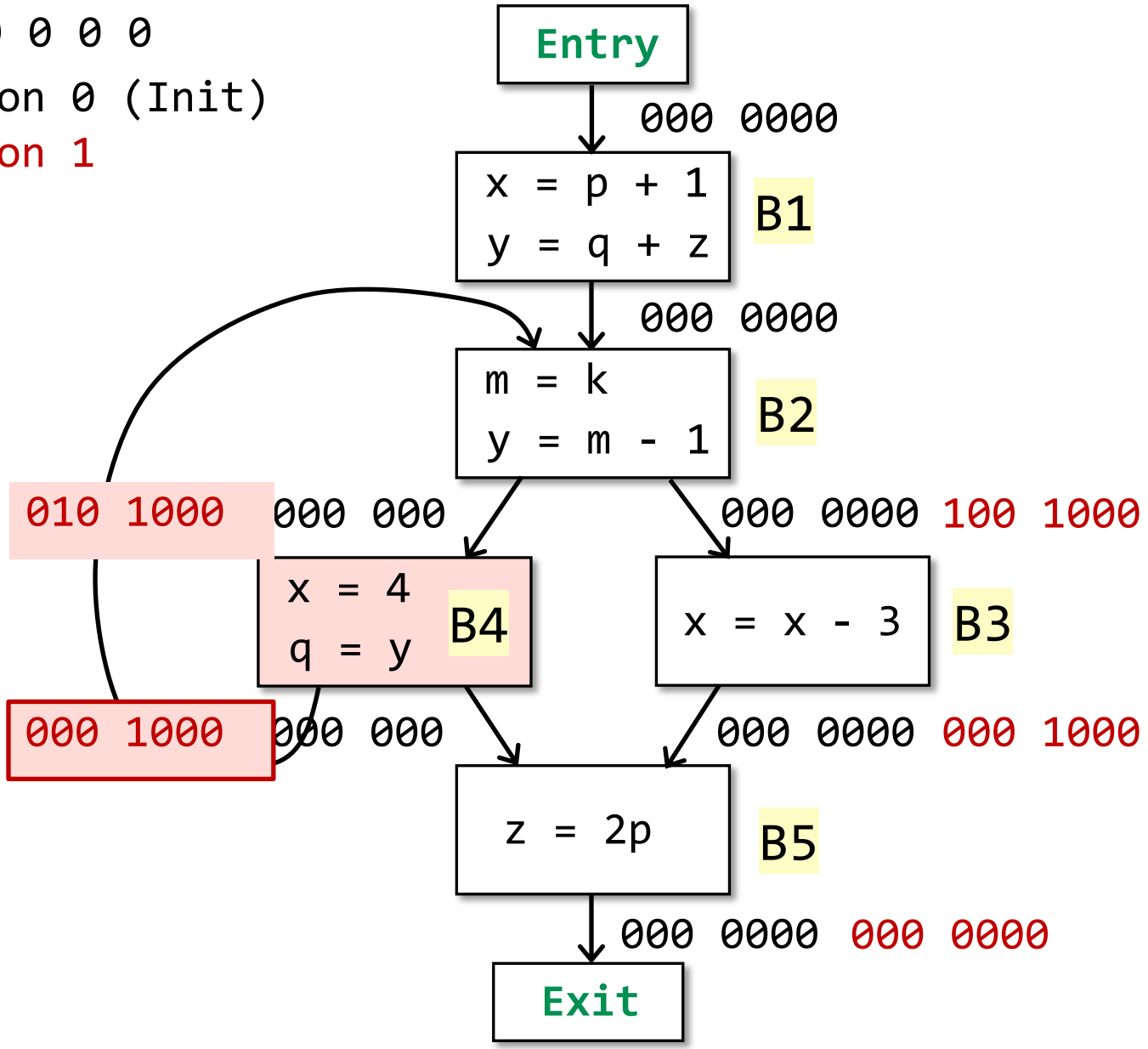
Iteration 1

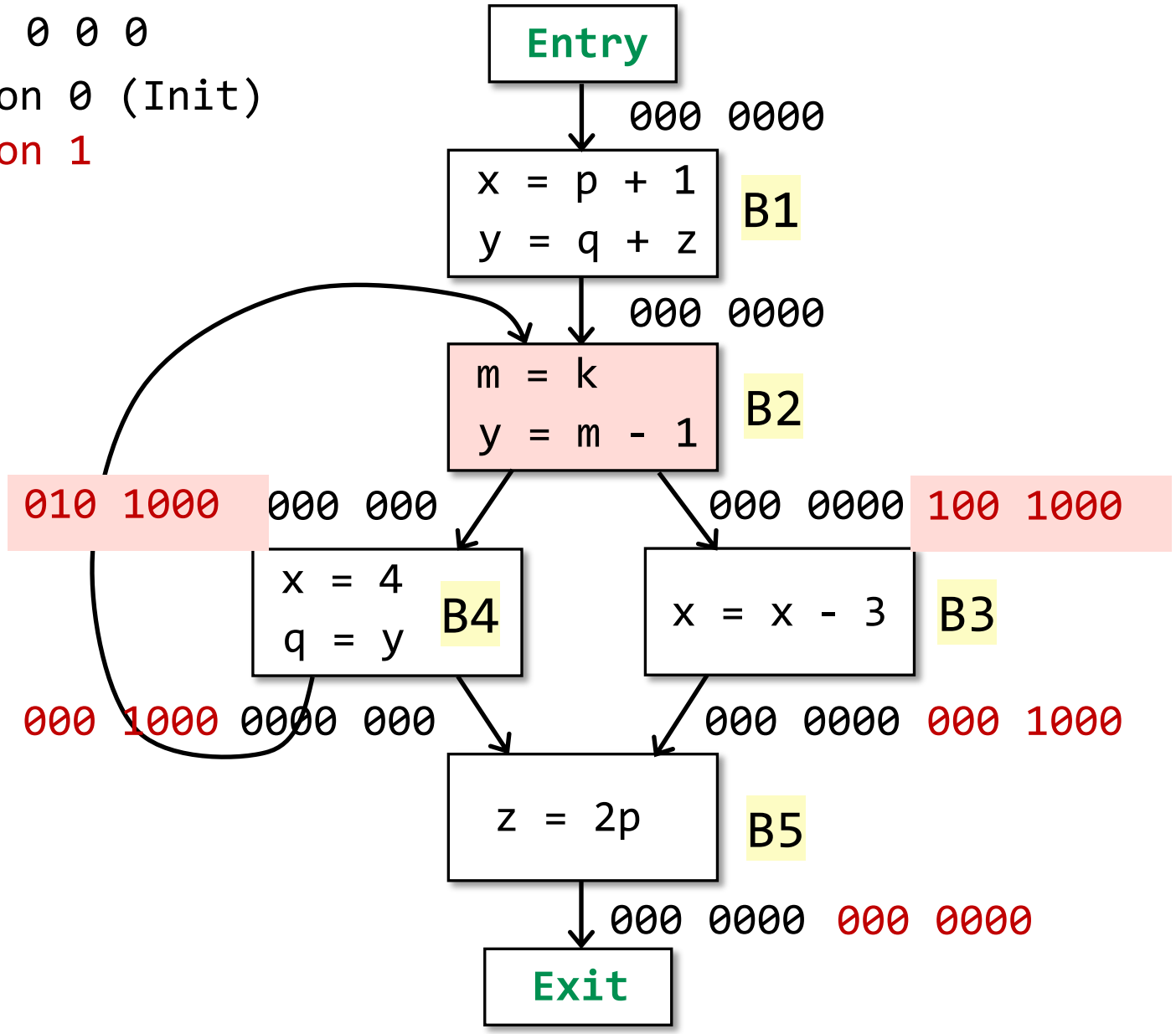


x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1



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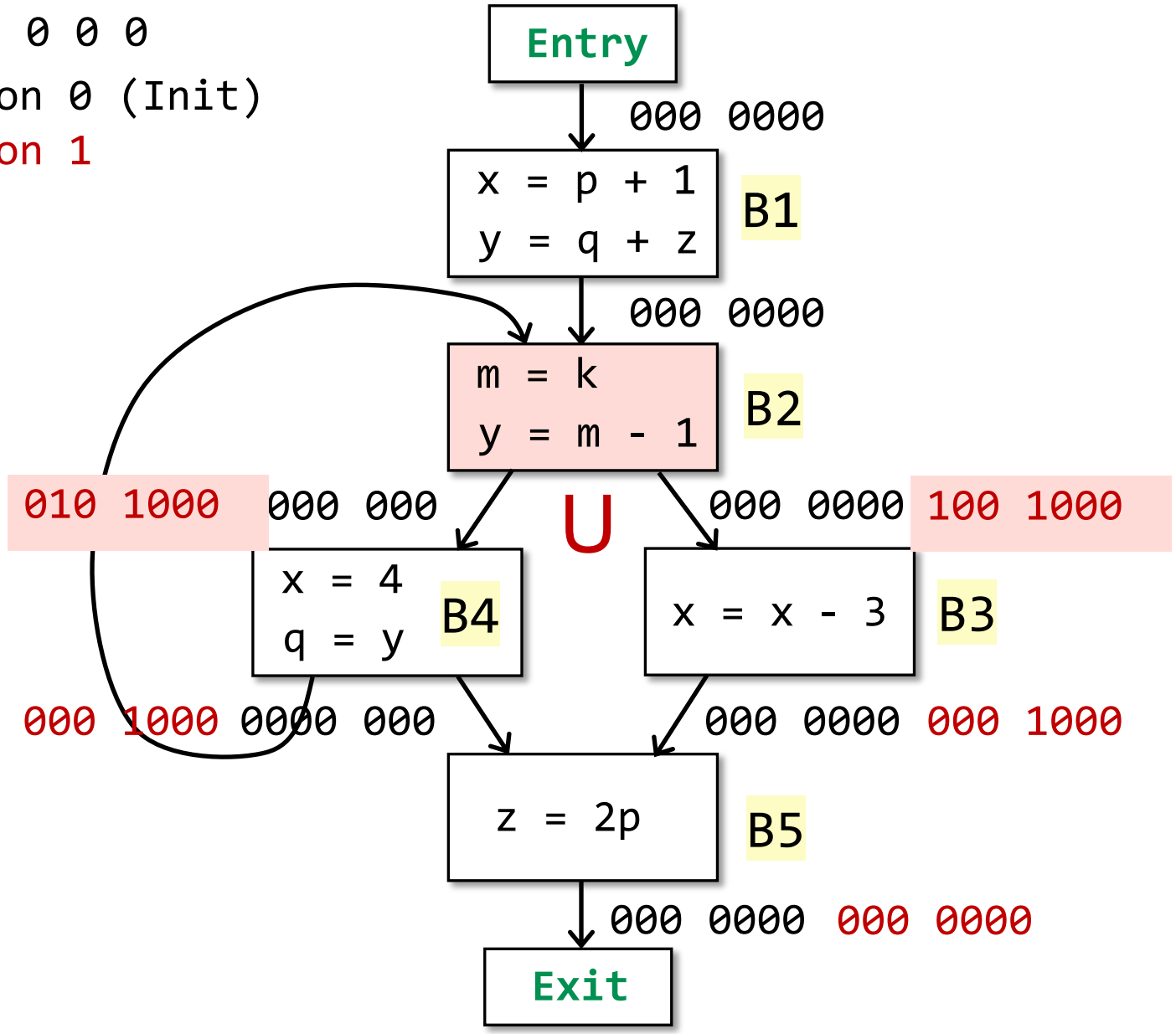
Iteration 1

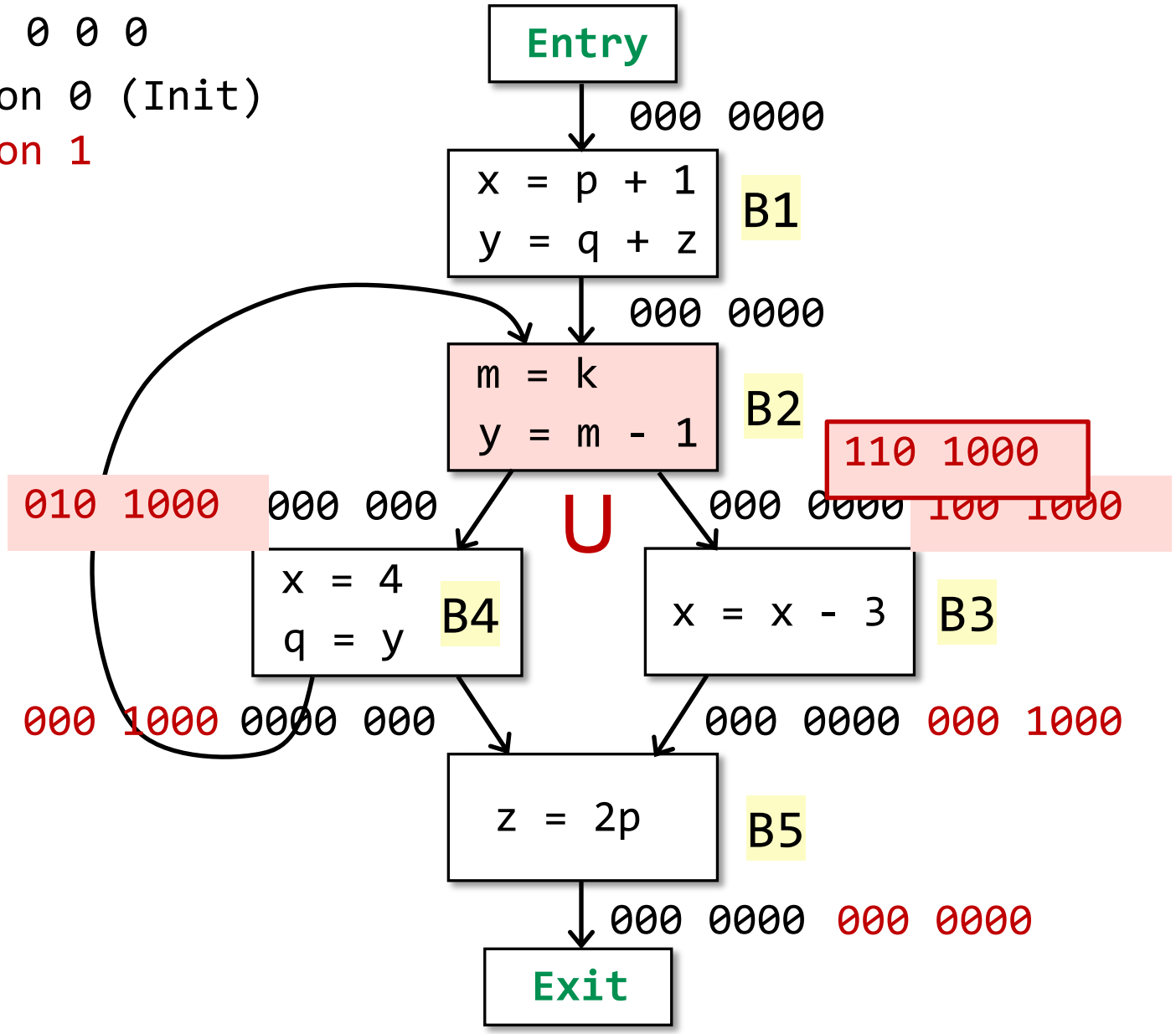


x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1



x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

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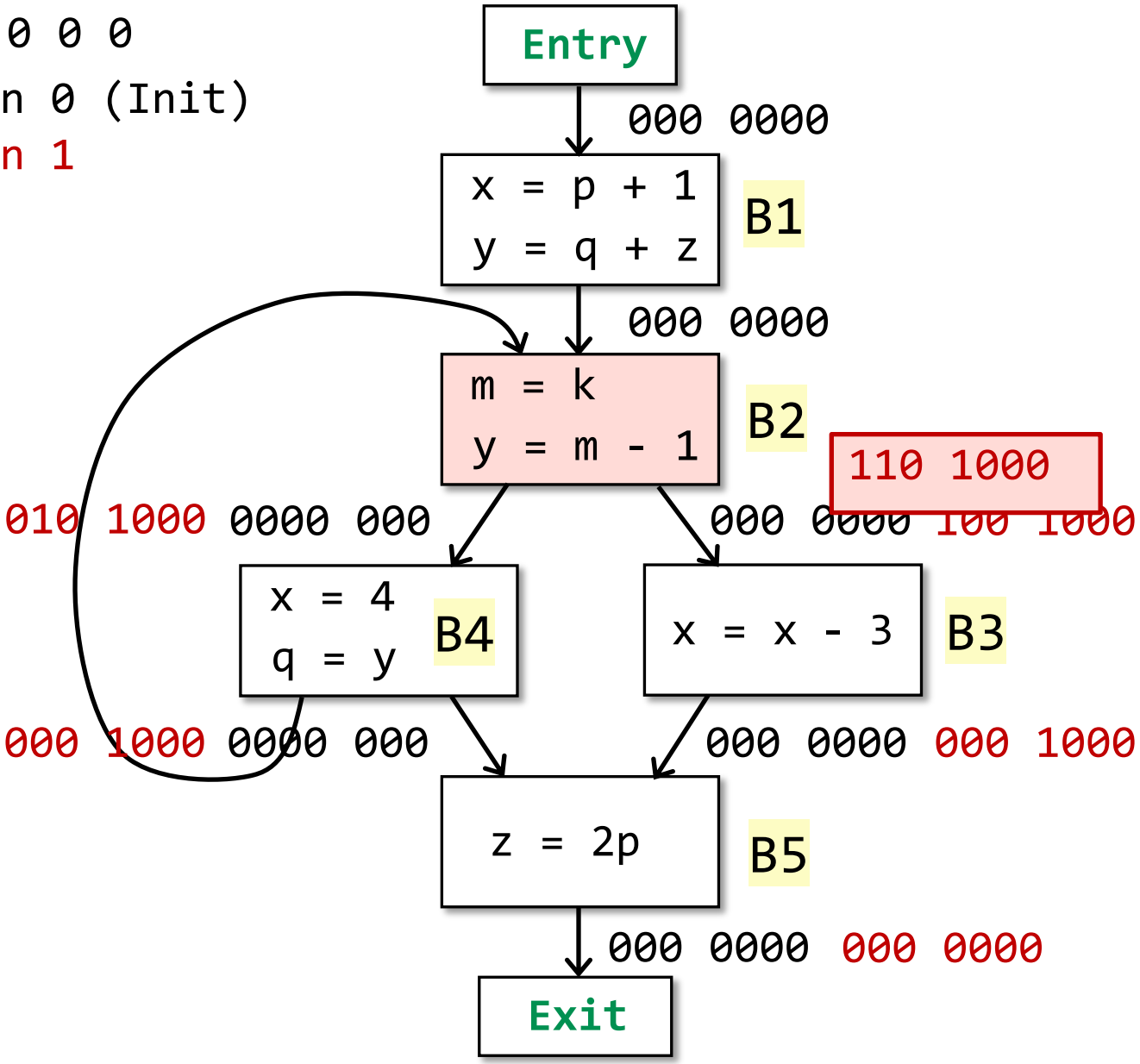
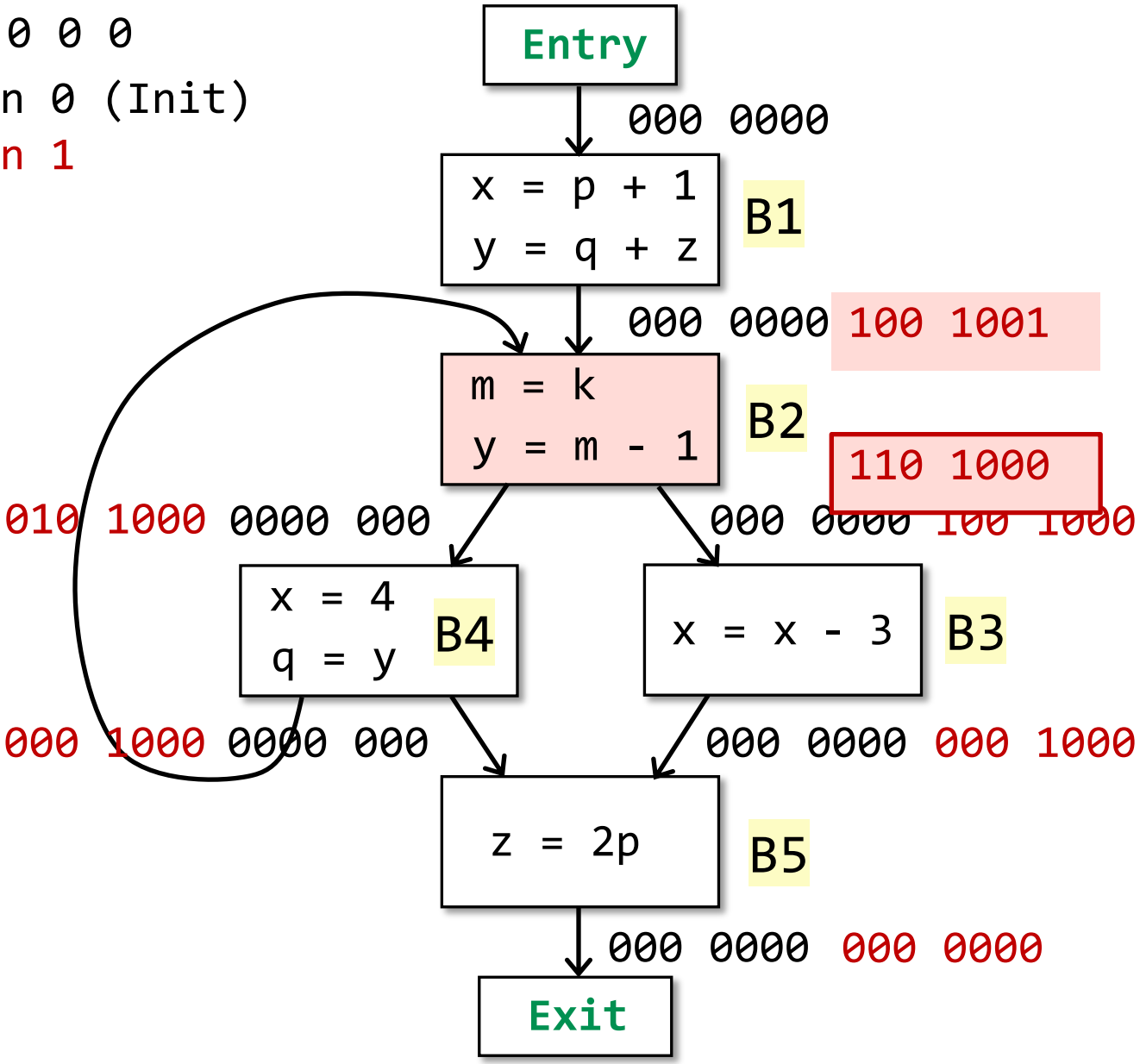


x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1

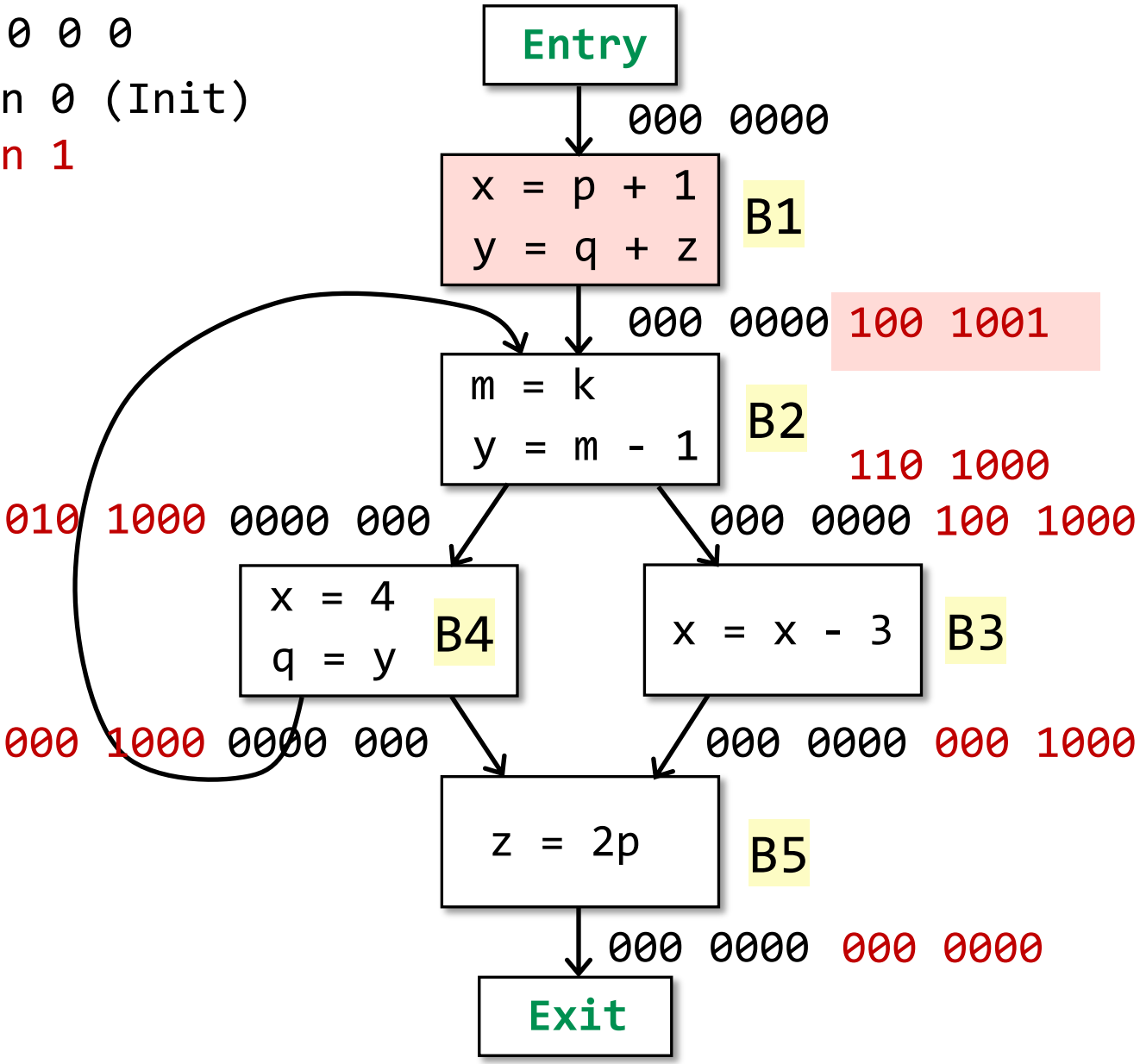


x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1

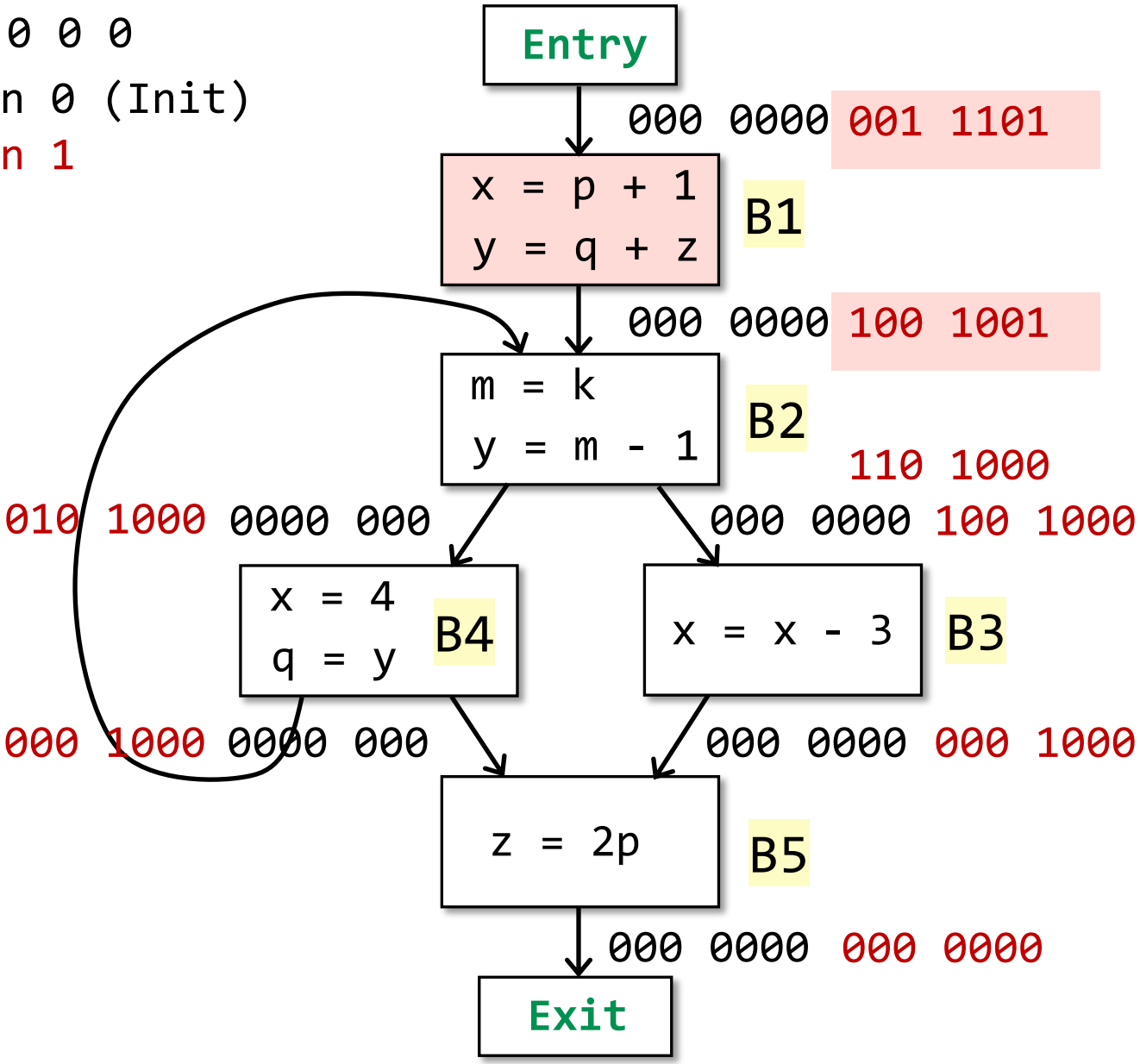


x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1

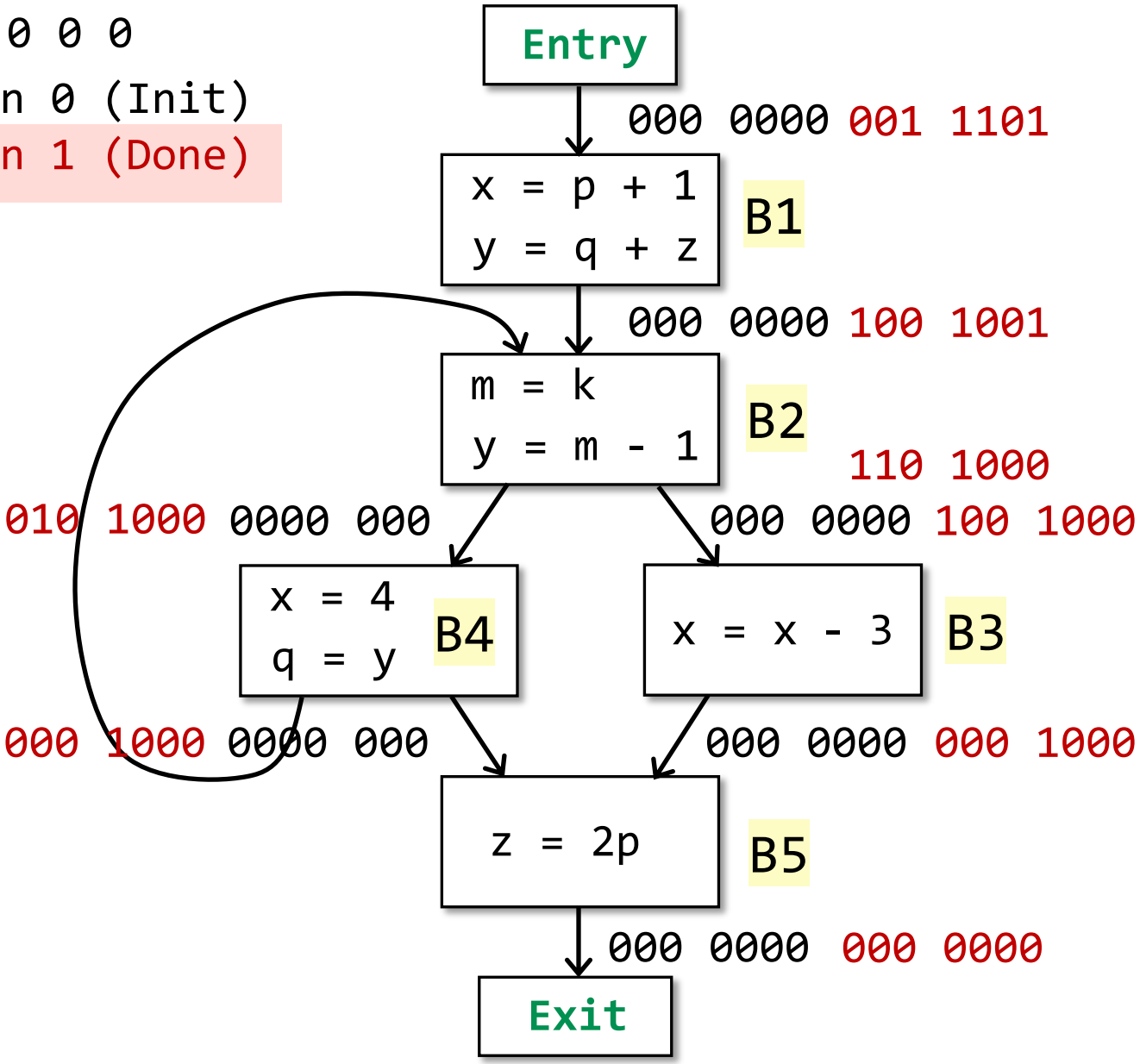


x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

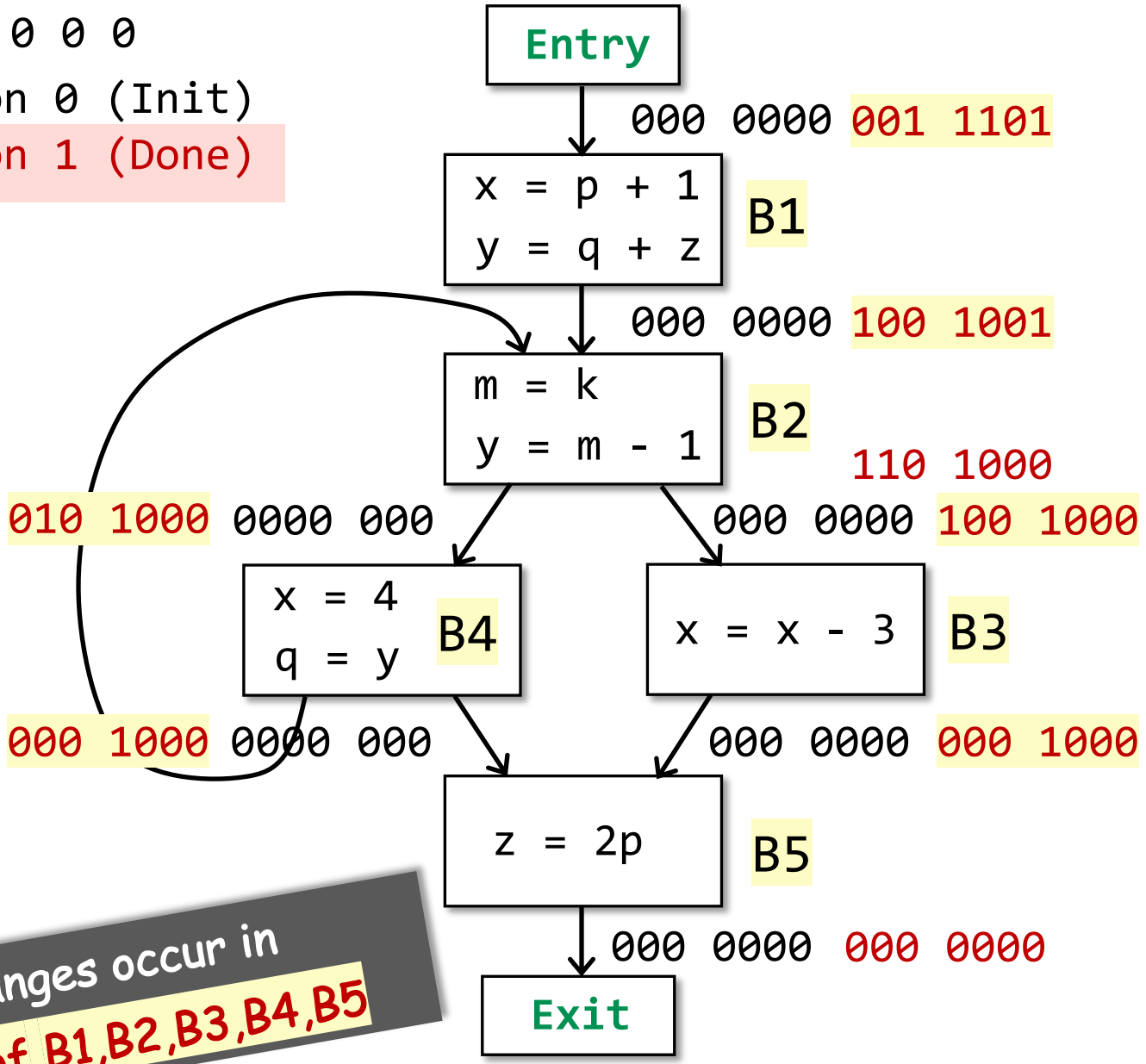


x y z p q m k

0 0 0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)



Changes occur in IN[] of B1,B2,B3,B4,B5

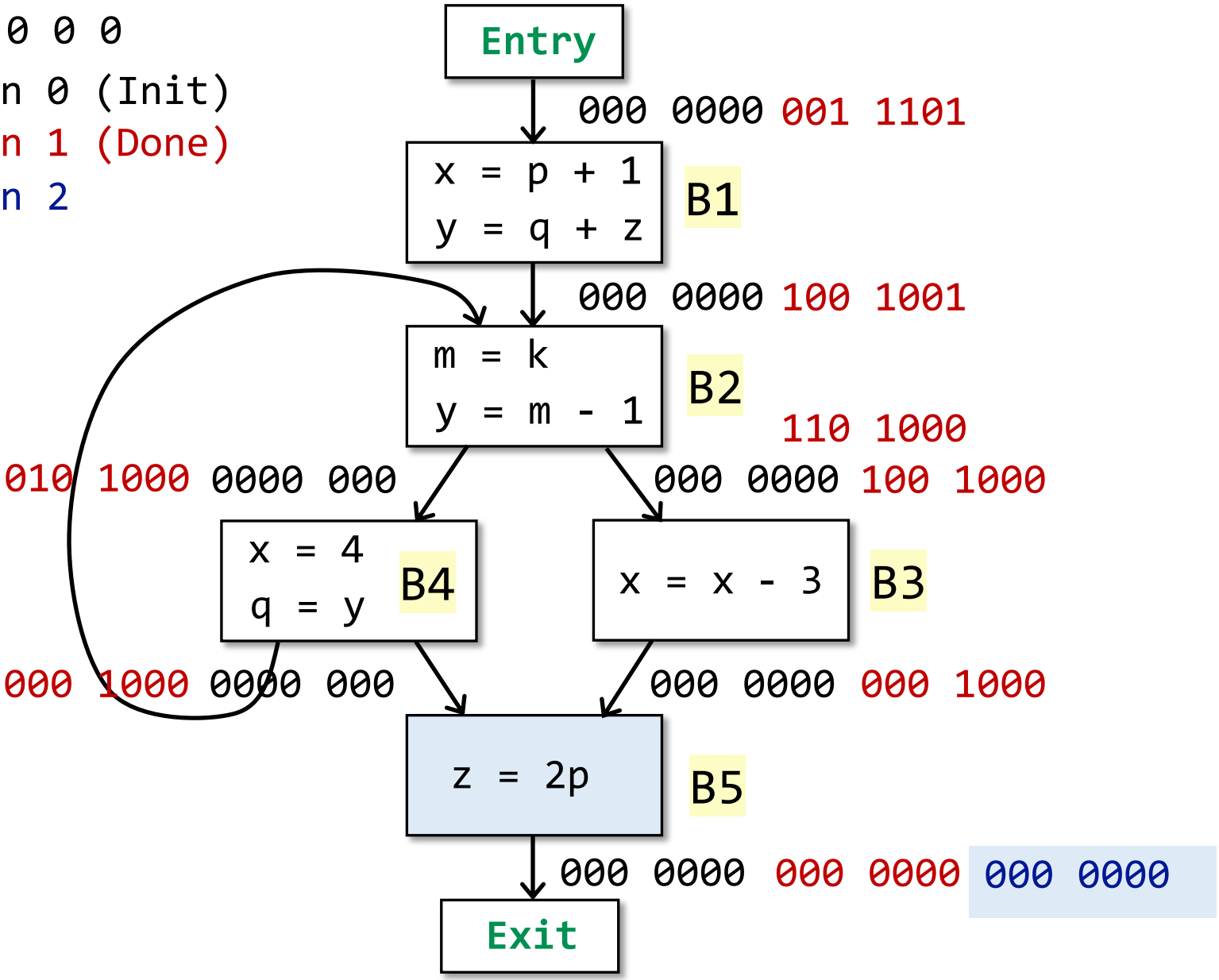
x y z p q m k

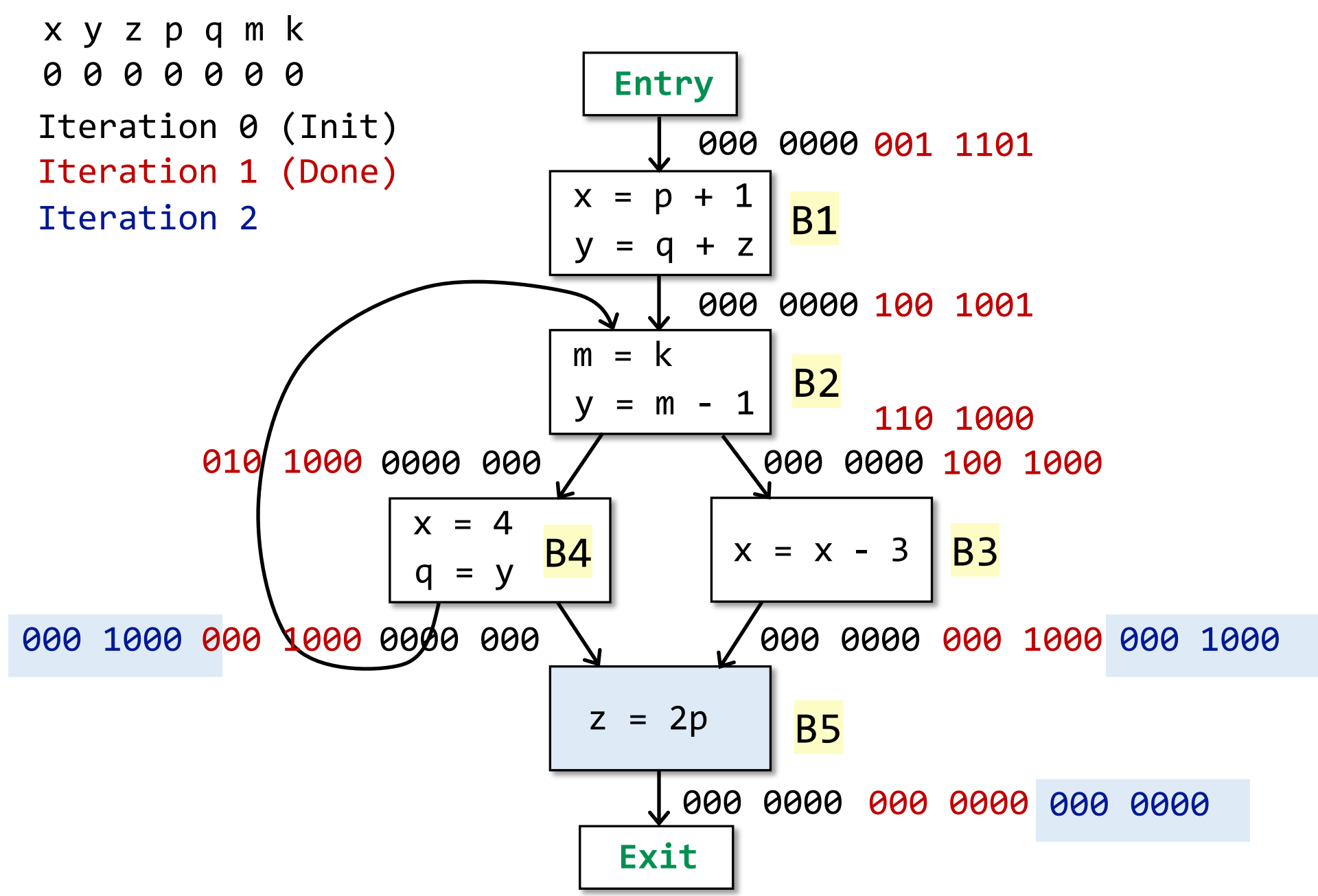
0 0 0 0 0 0 0

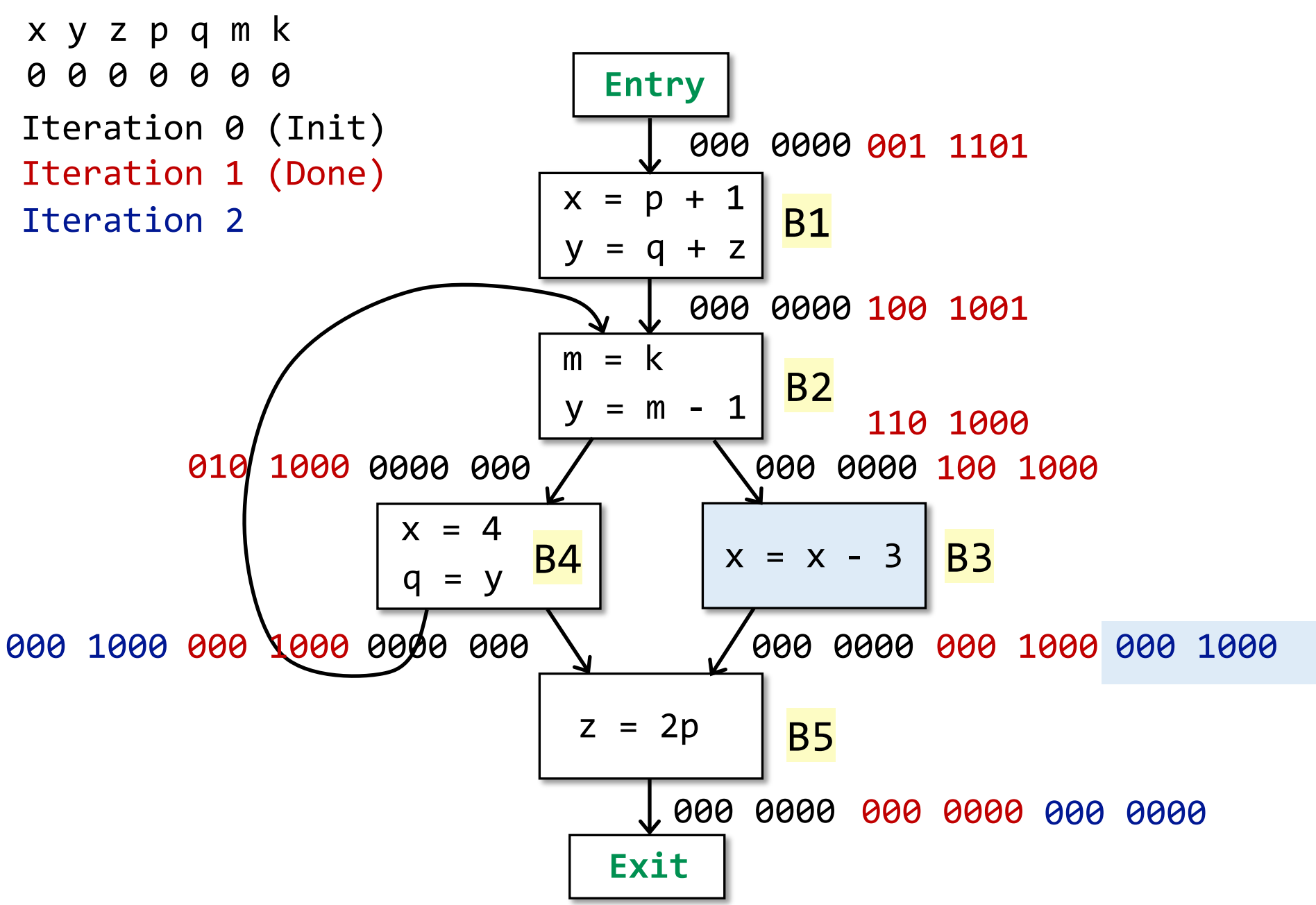
Iteration 0 (Init)

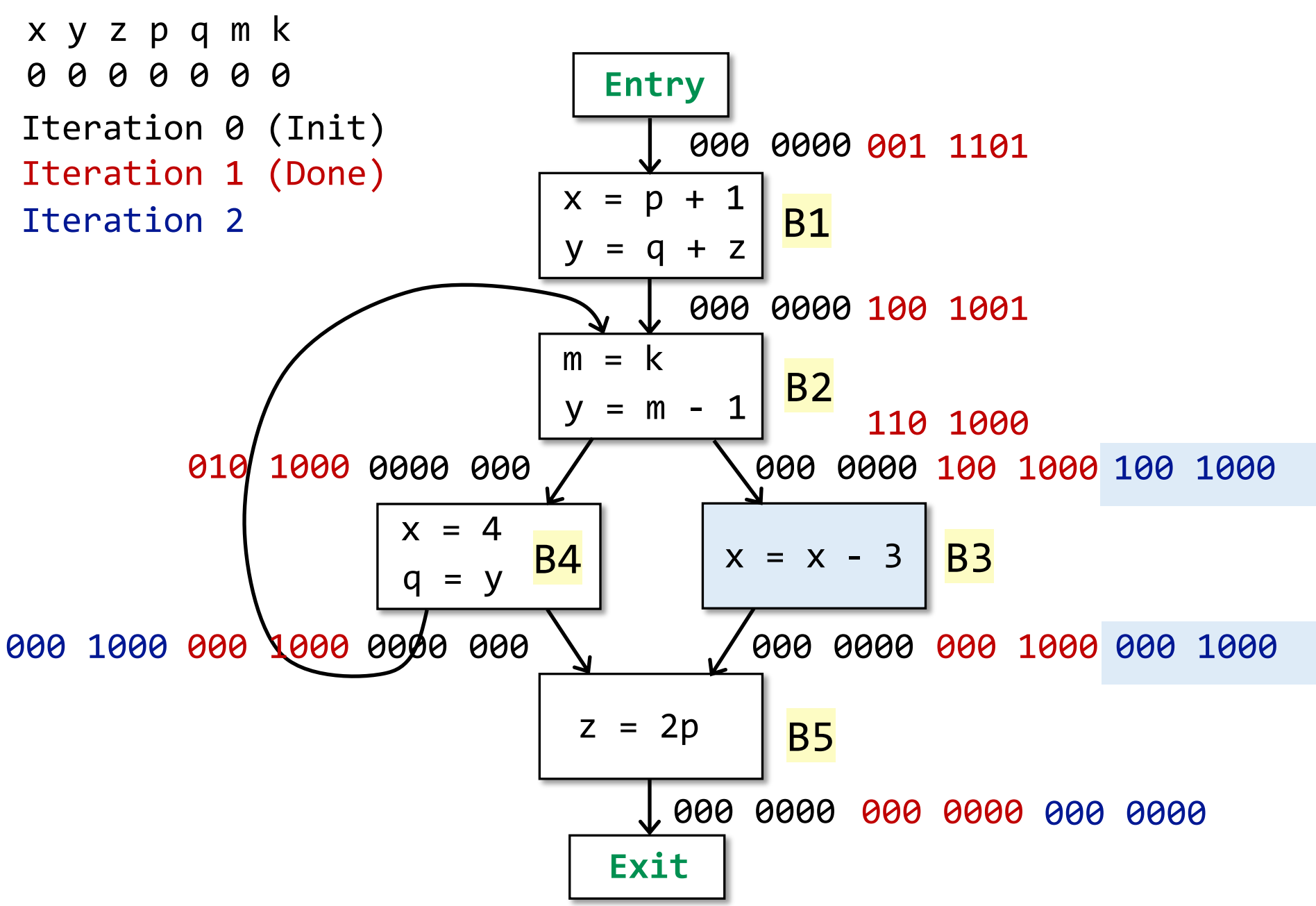
Iteration 1 (Done)

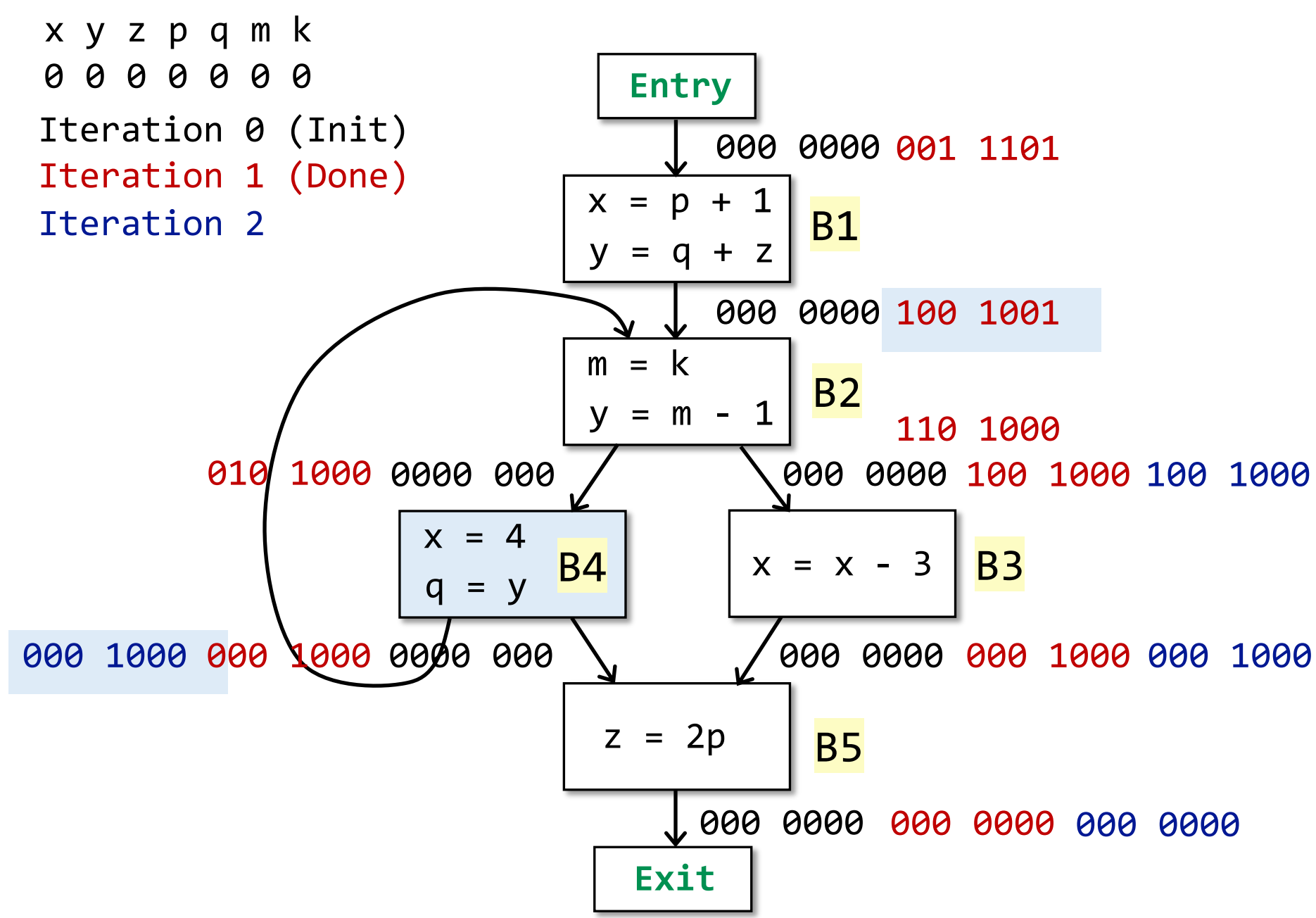
Iteration 2

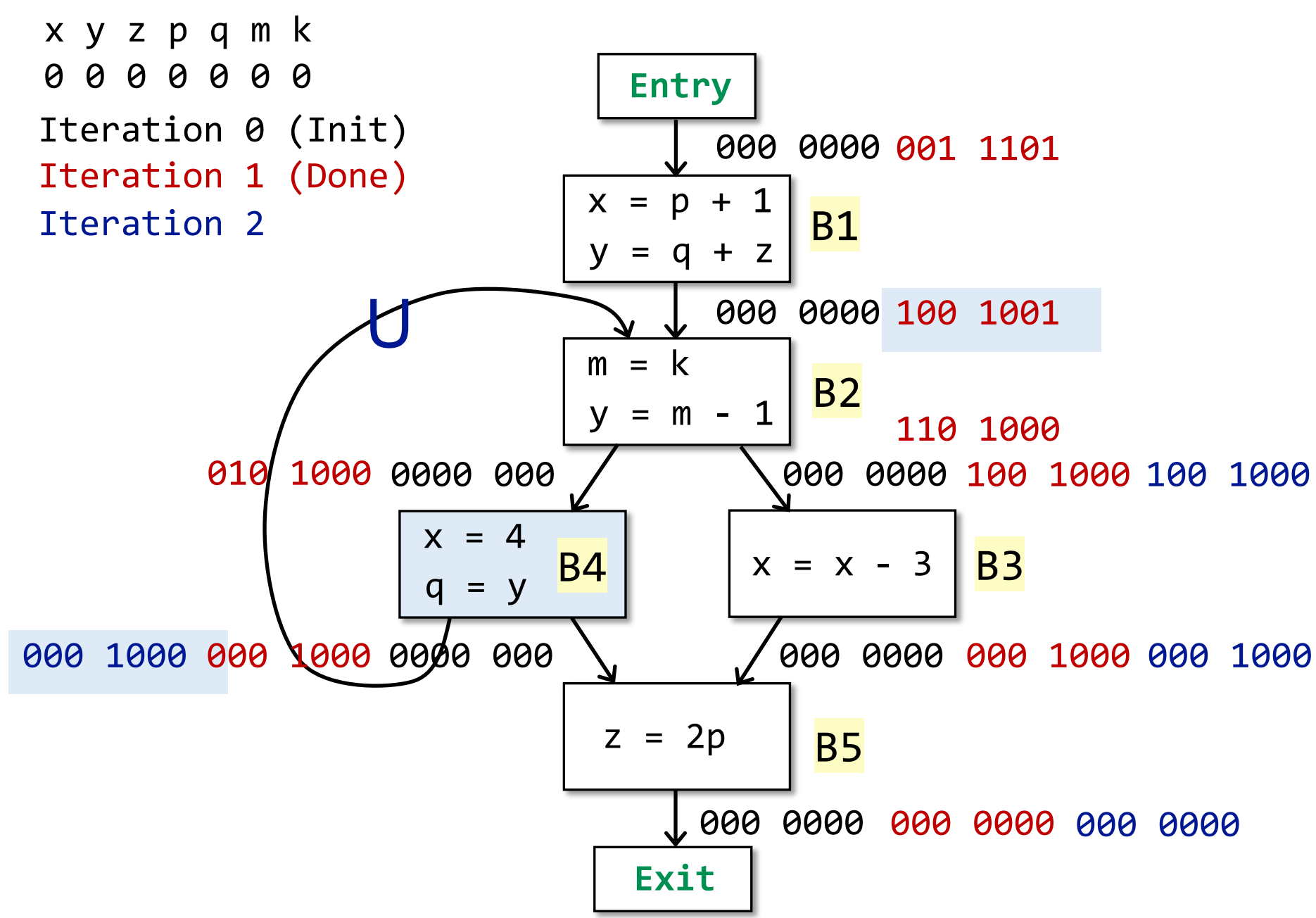


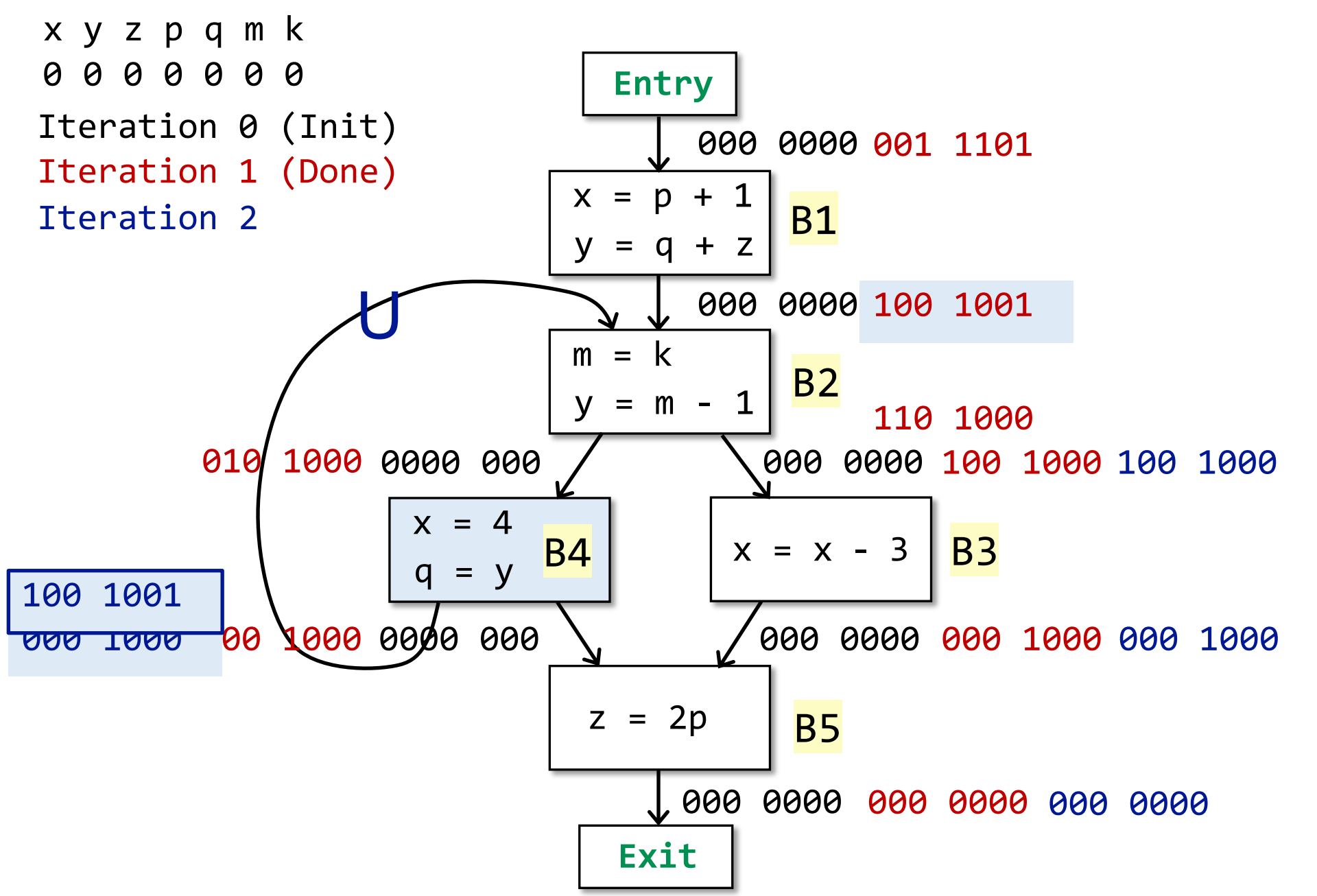

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1000 0000 000
000 0000 100 1000
x = 4
q = y
B4
x = x - 3
B3
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

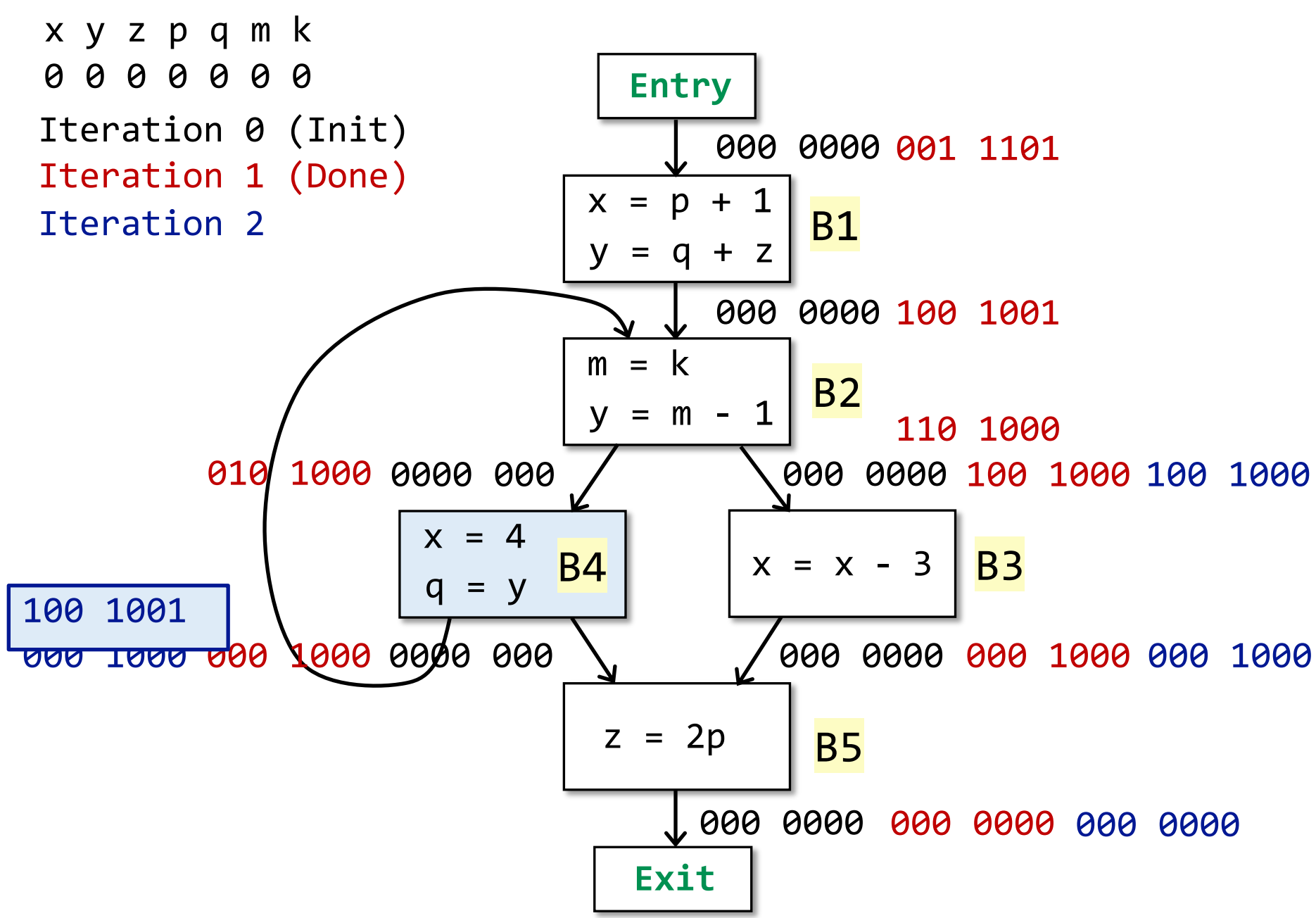

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1000 0000 000
000 0000 100 1000
x = 4
q = y
B4
x = x - 3
B3
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

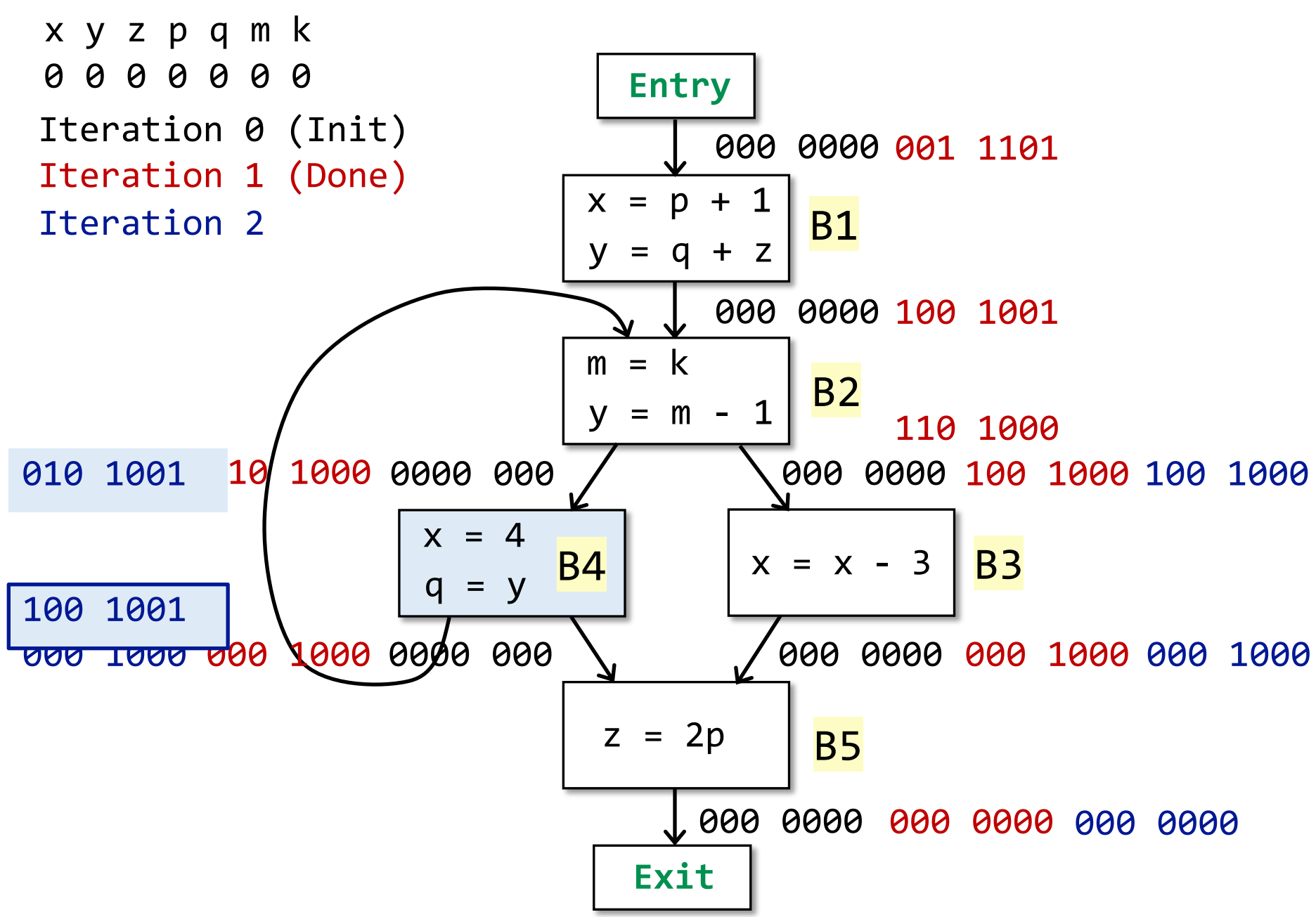

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

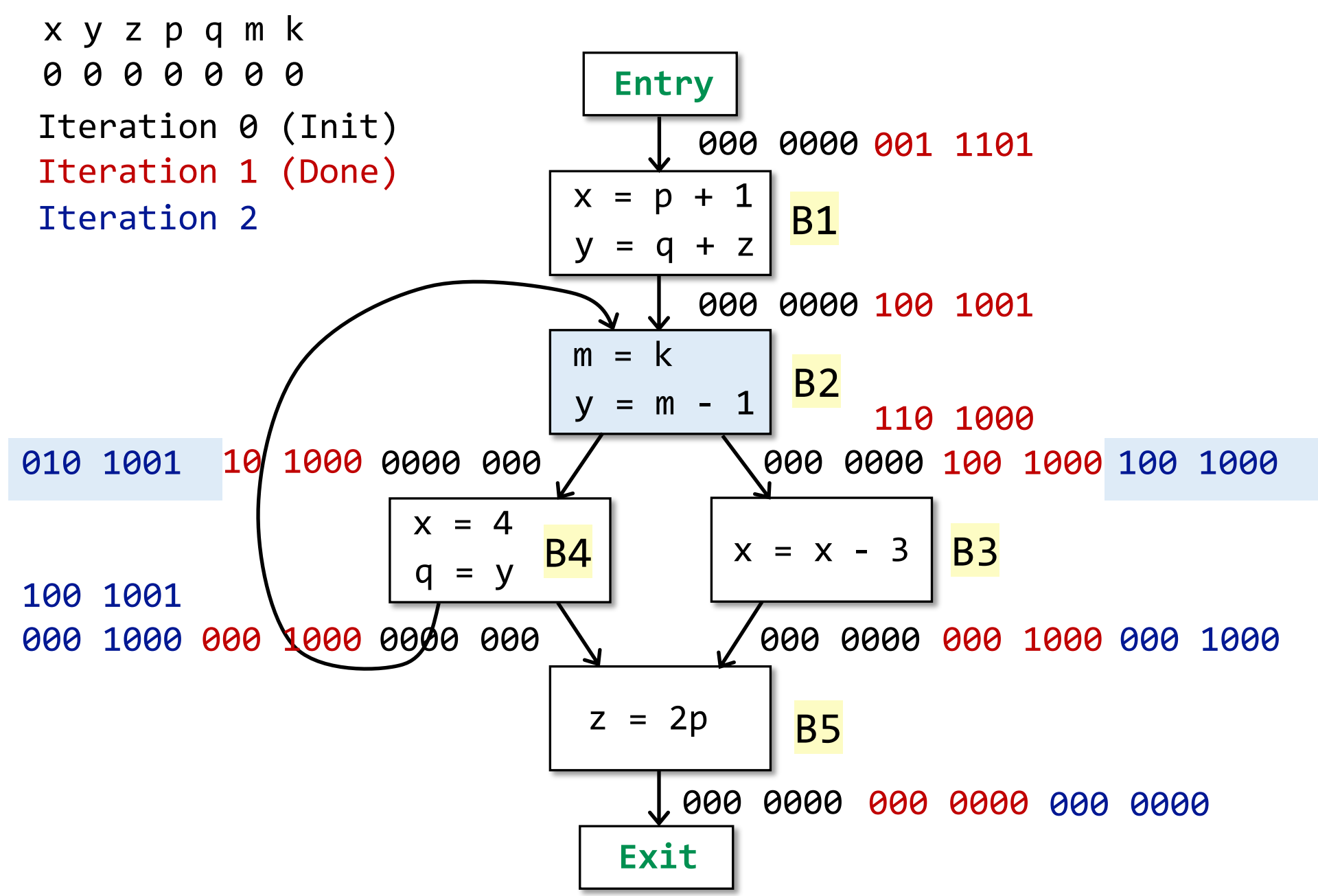

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

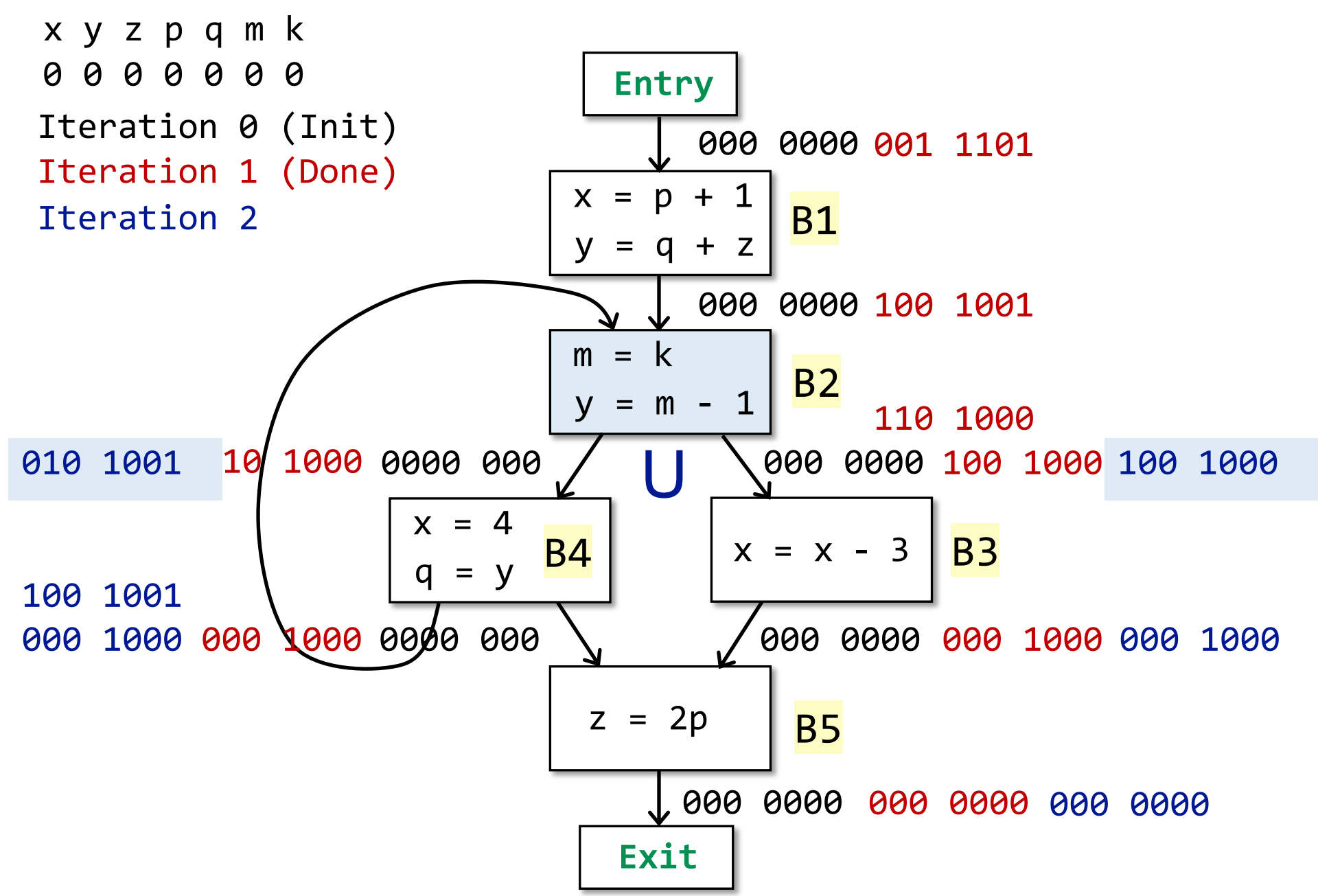

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
U
m = k
y = m - 1
B2
110 1000
010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

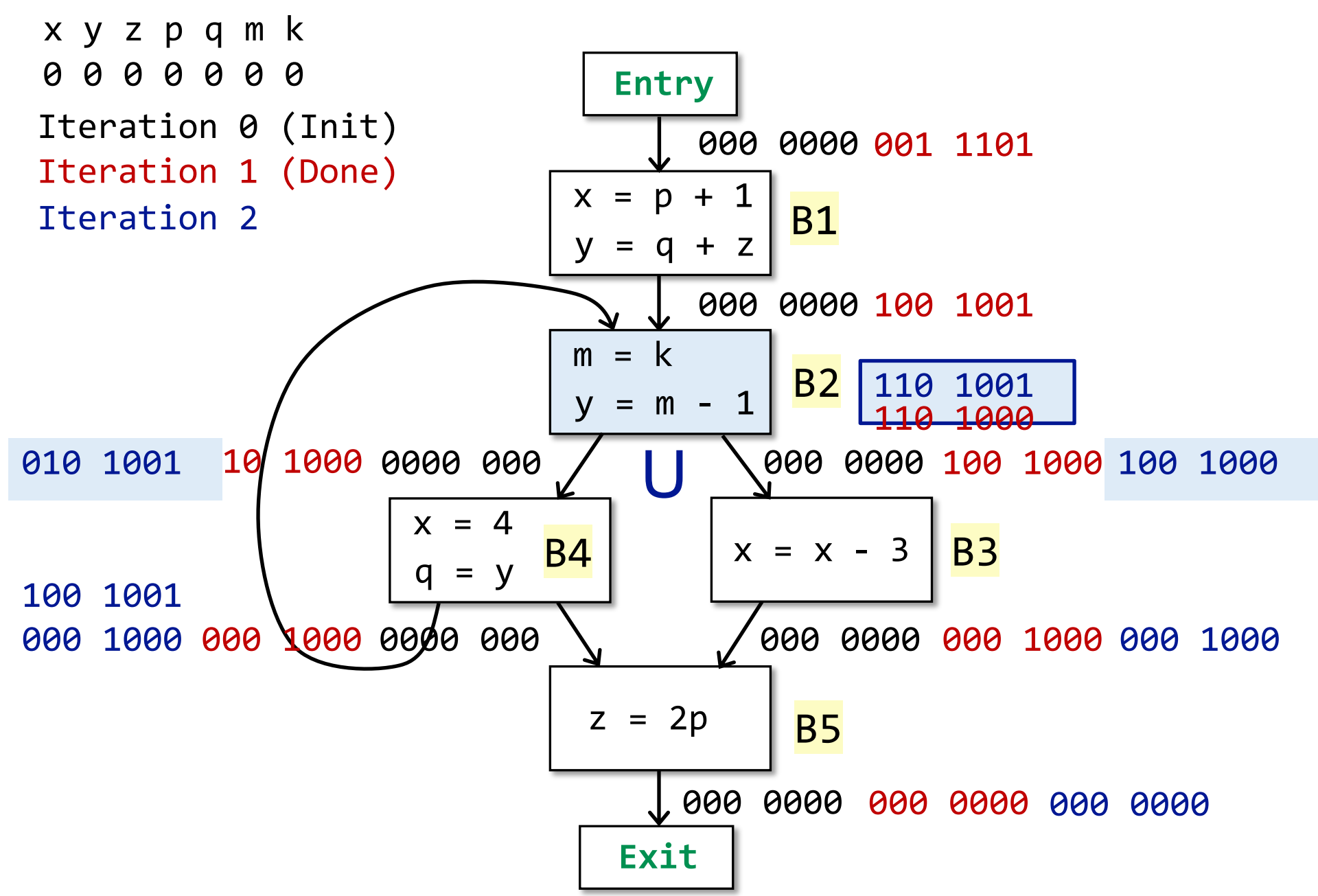

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000
00 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

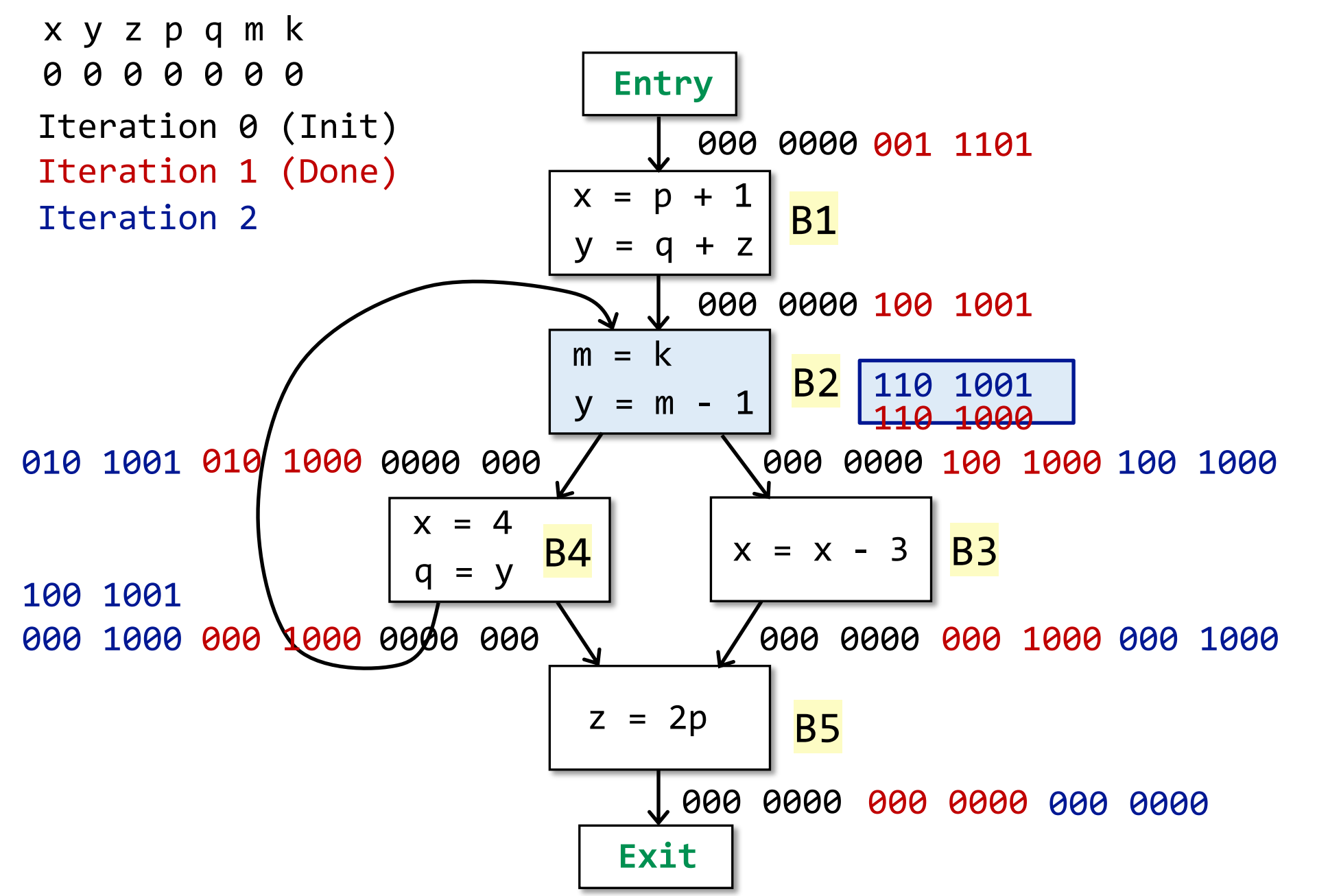

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

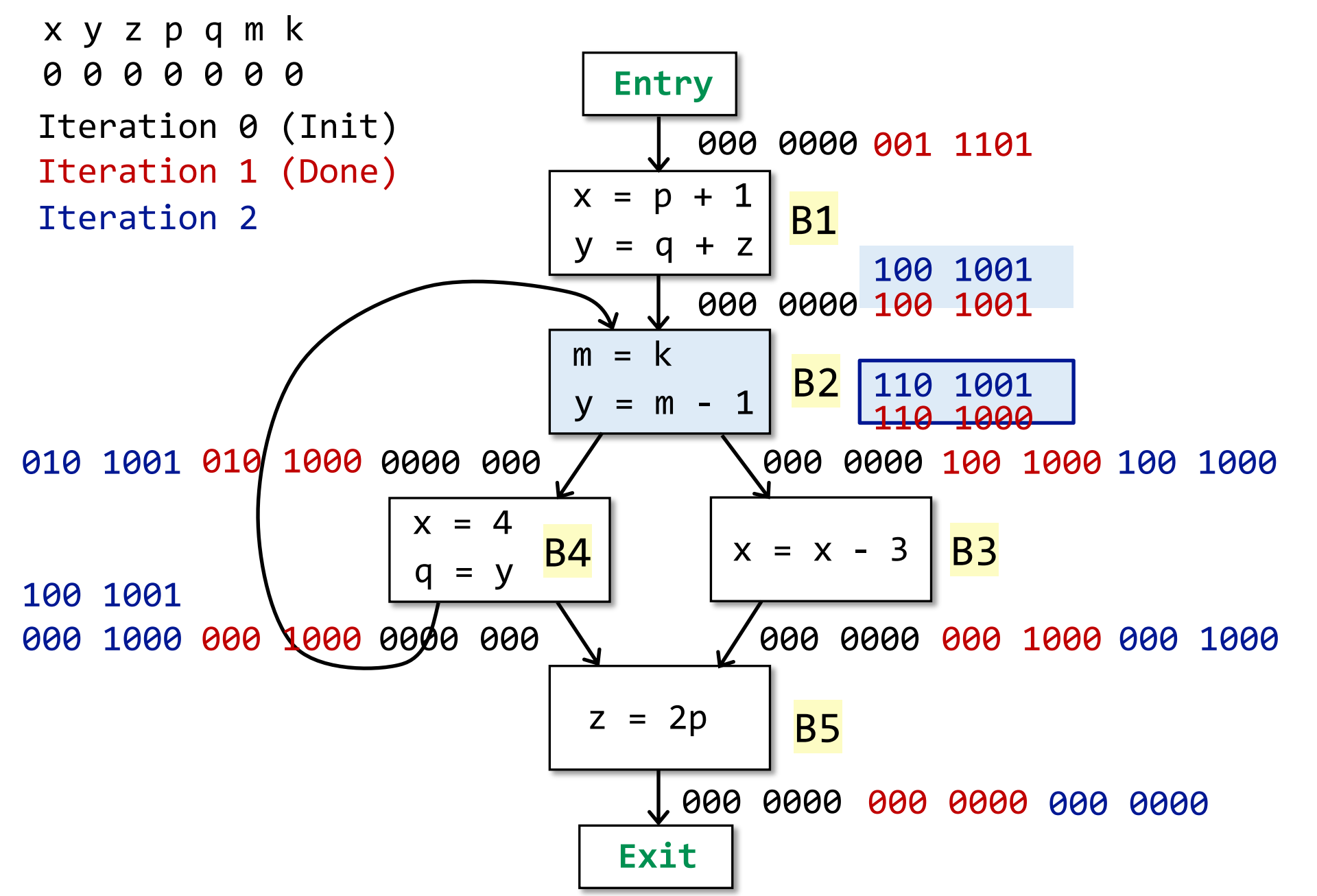

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1001
10 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

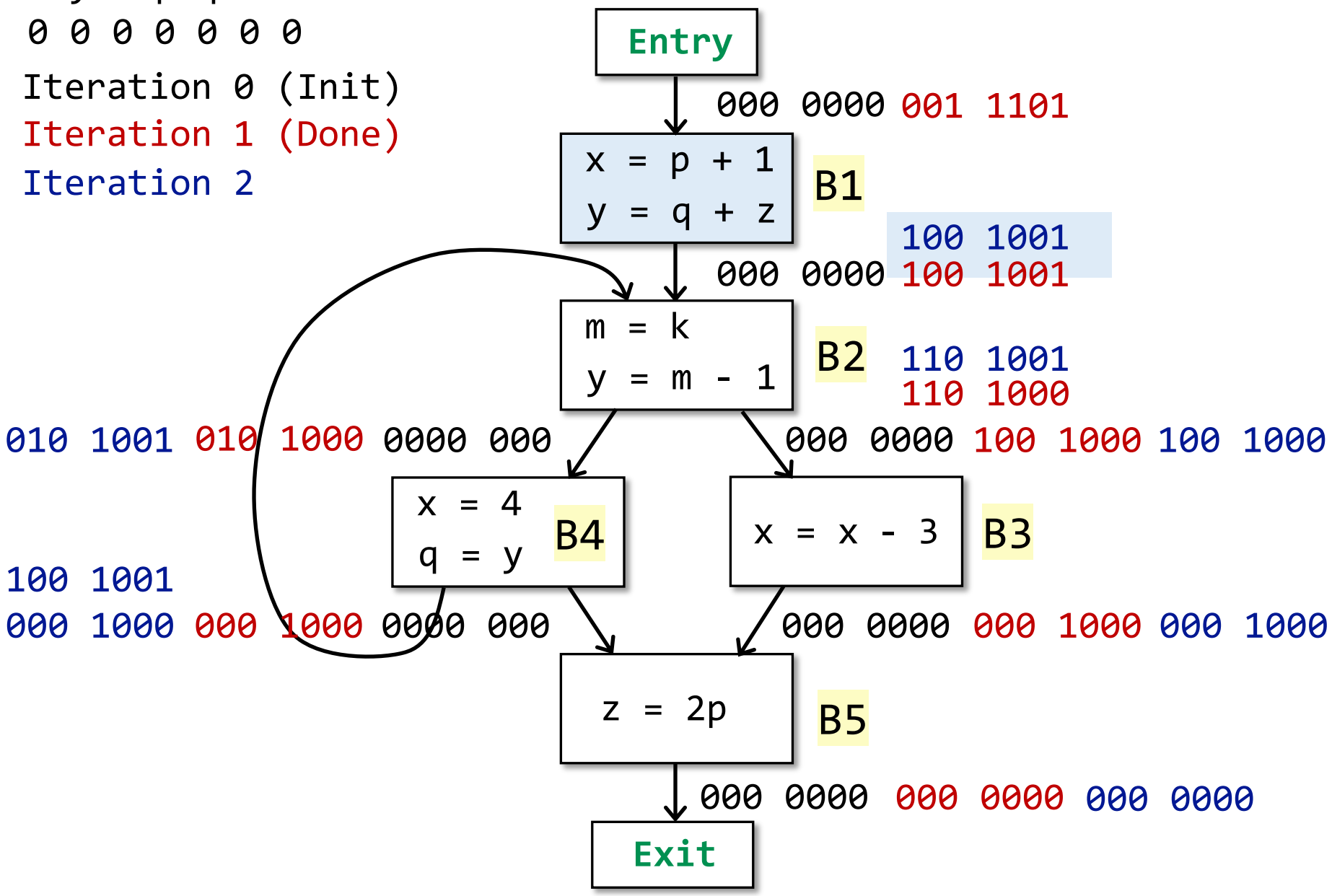

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1001
10 1000 0000 000
000 0000 100 1000
100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

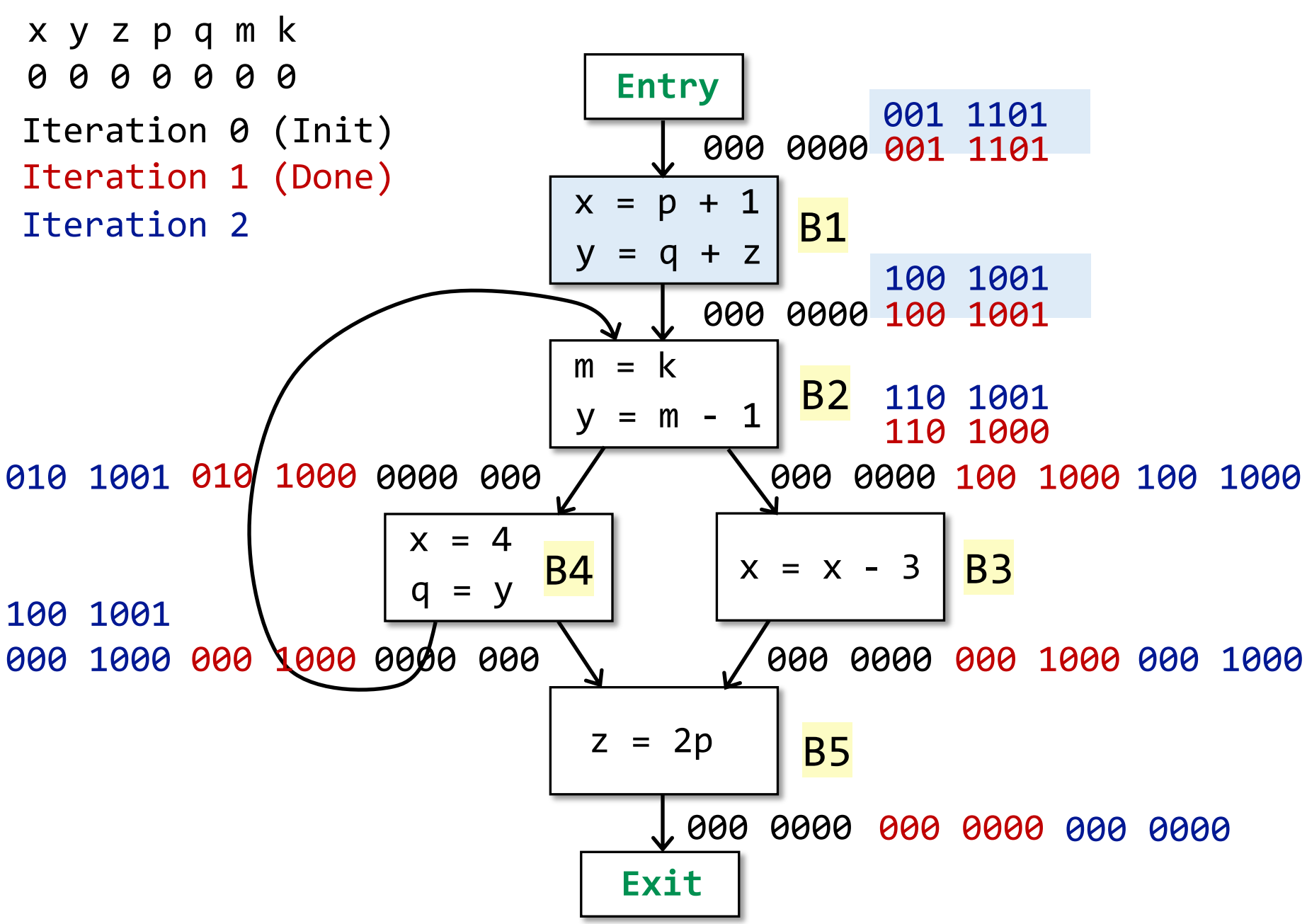

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1000
010 1001
10 1000 0000 000
U
000 0000 100 1000
100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

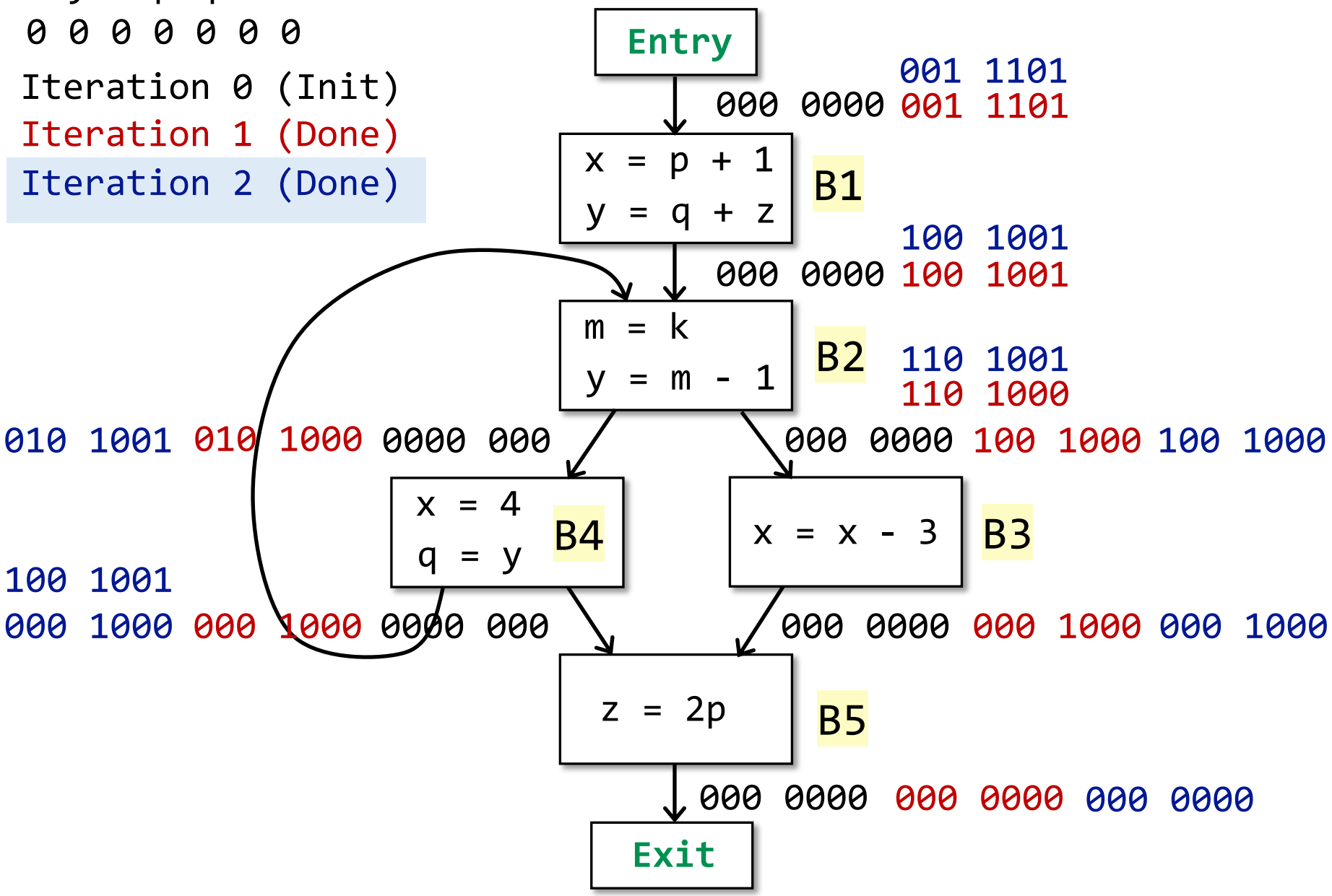

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001
10 1000 0000 000
U
000 0000 100 1000
100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

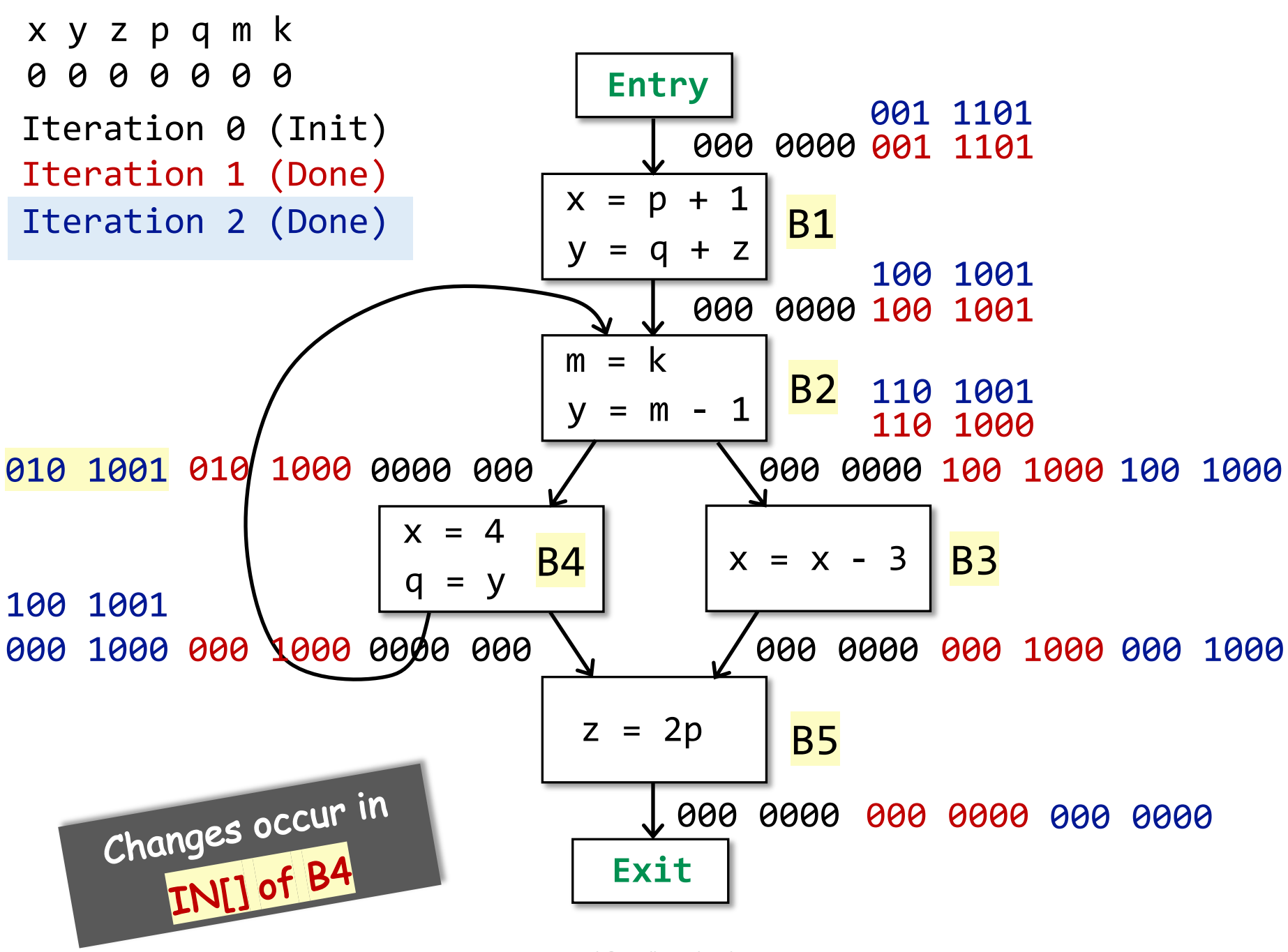

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

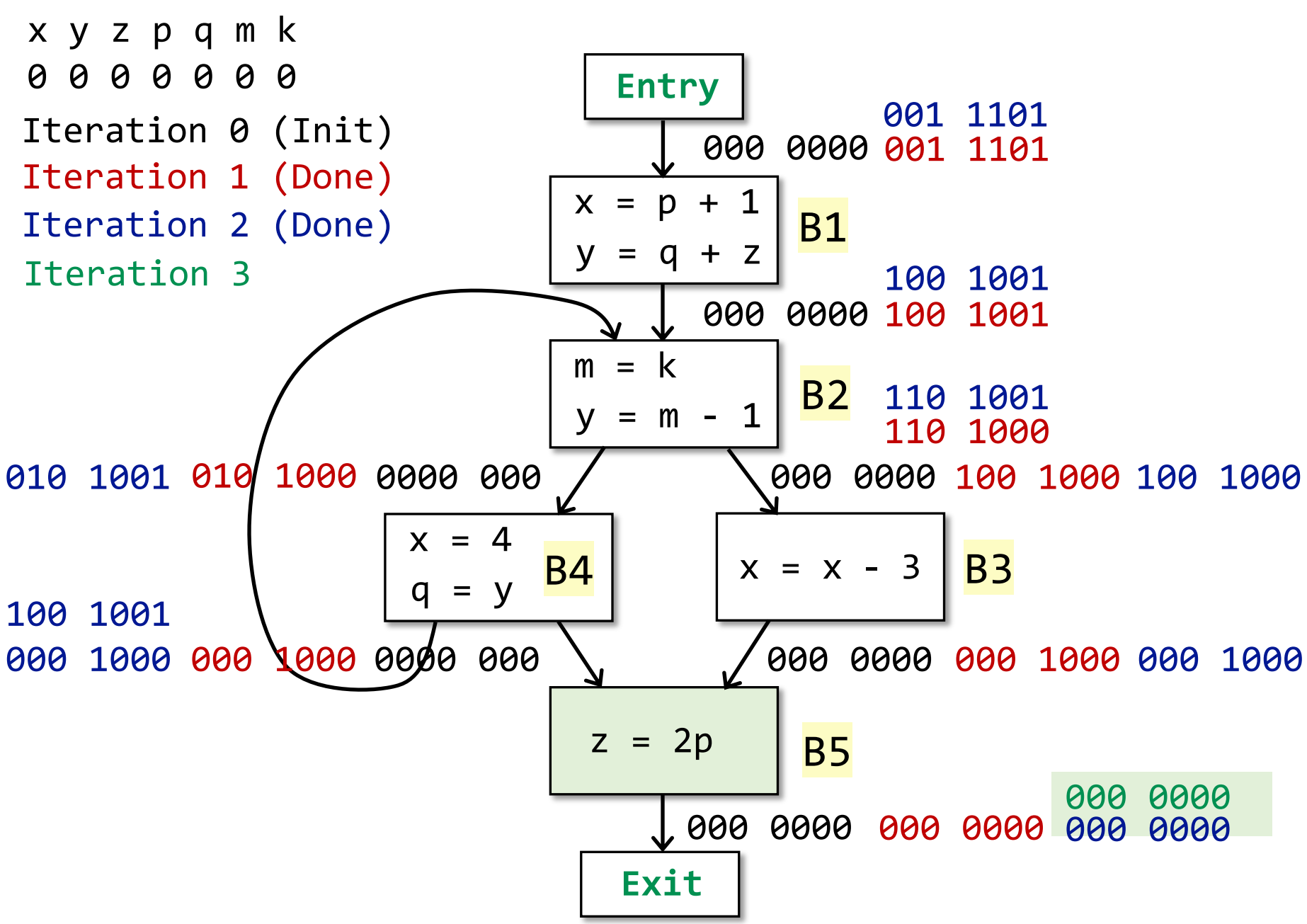

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

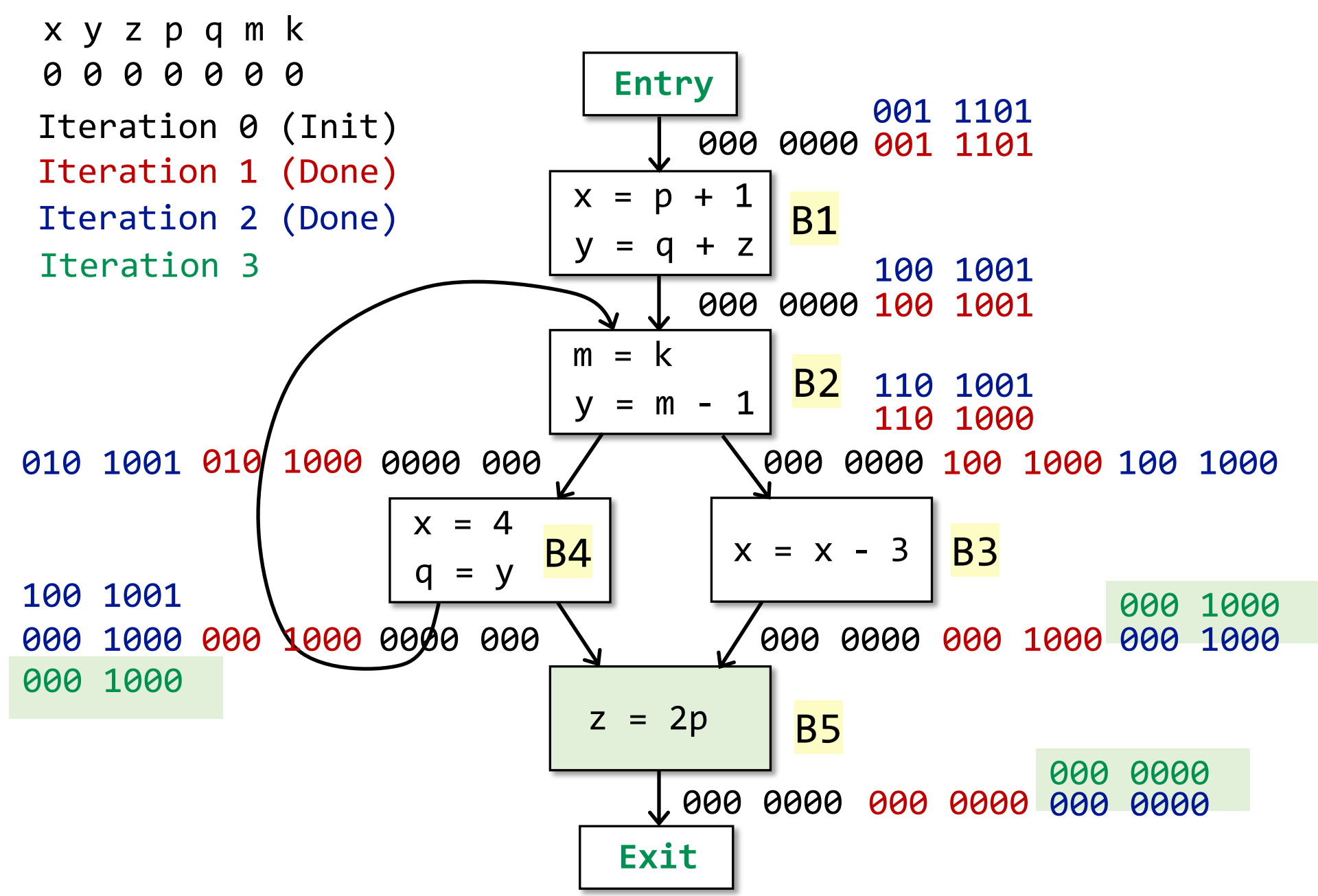

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

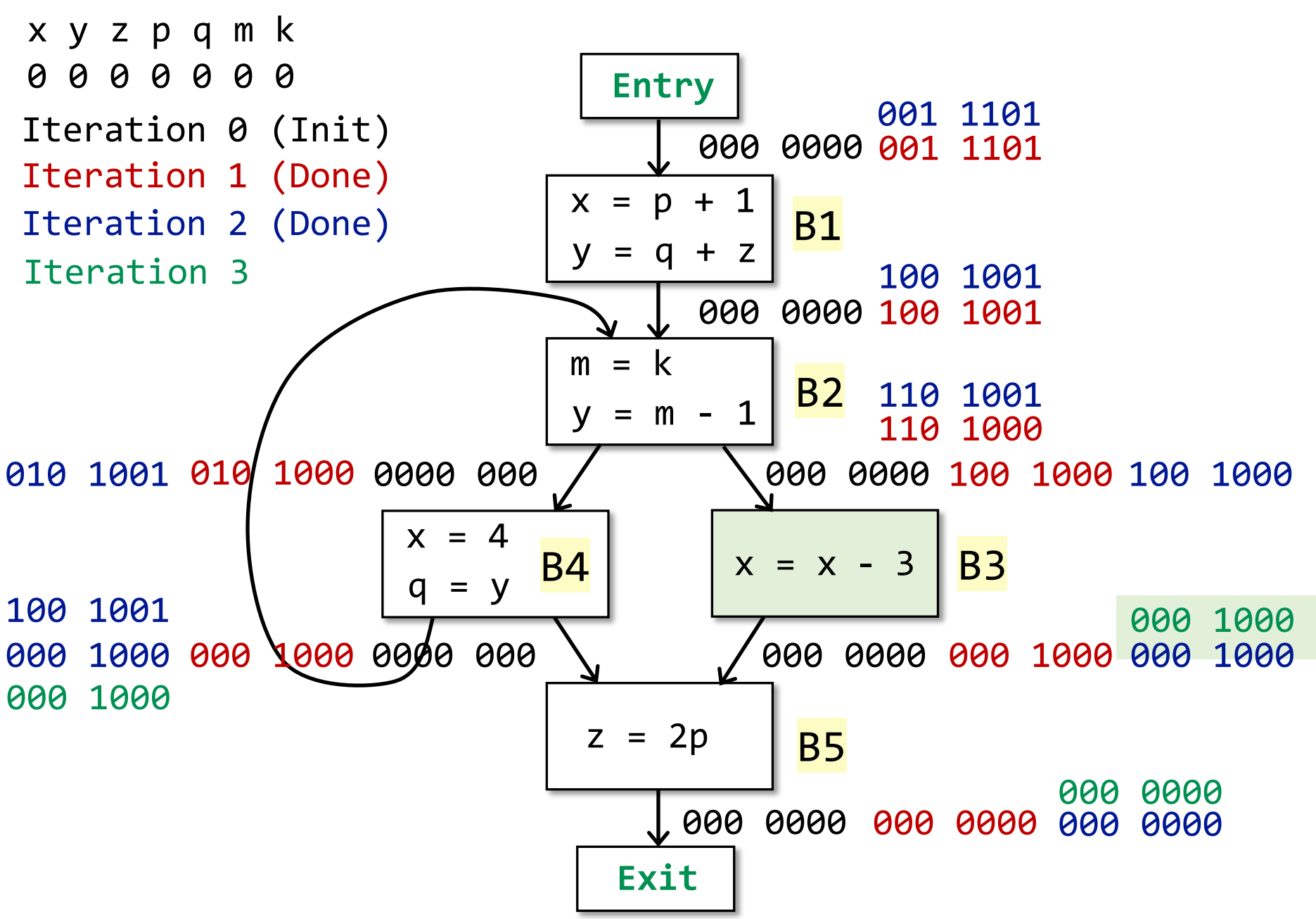

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

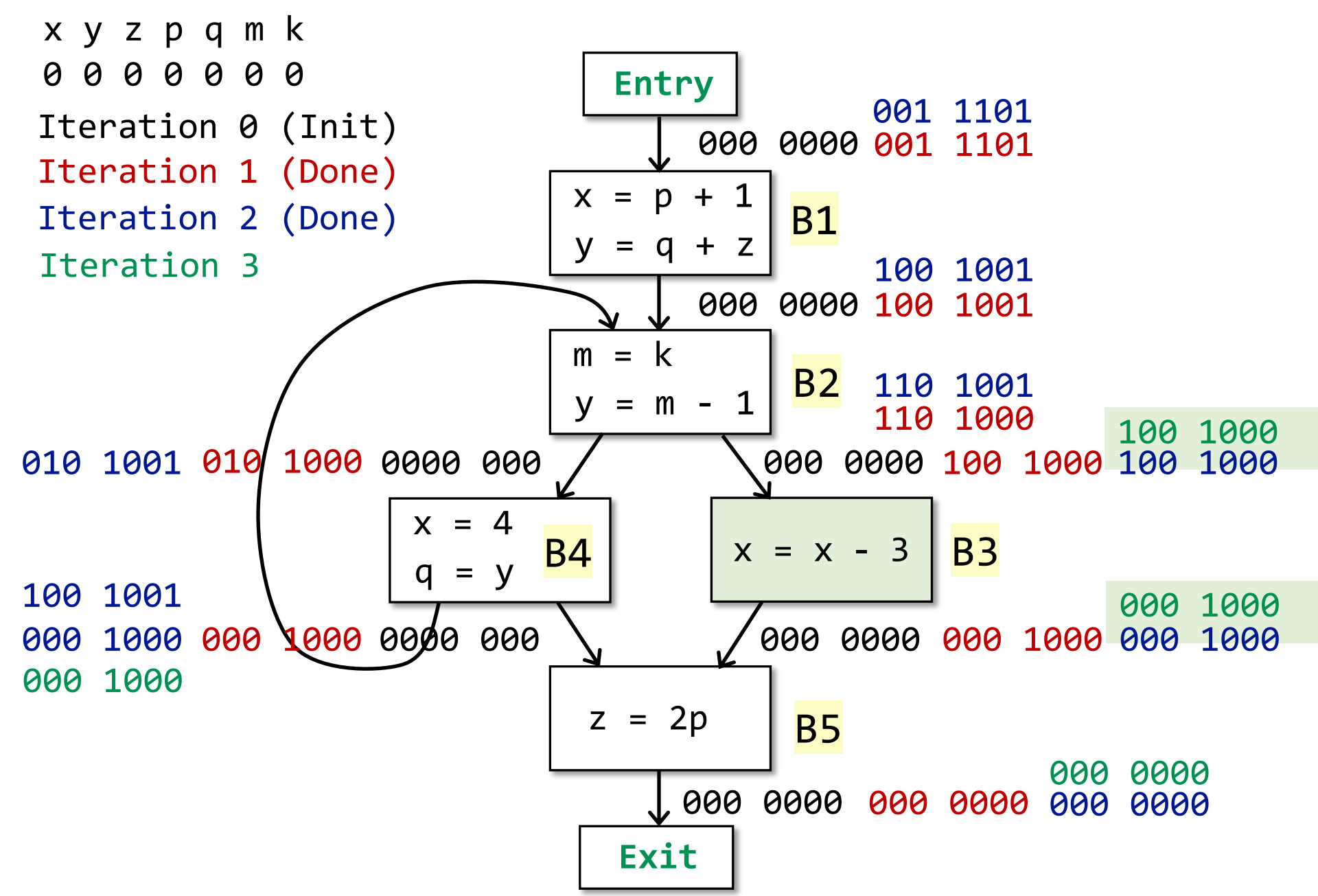

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit

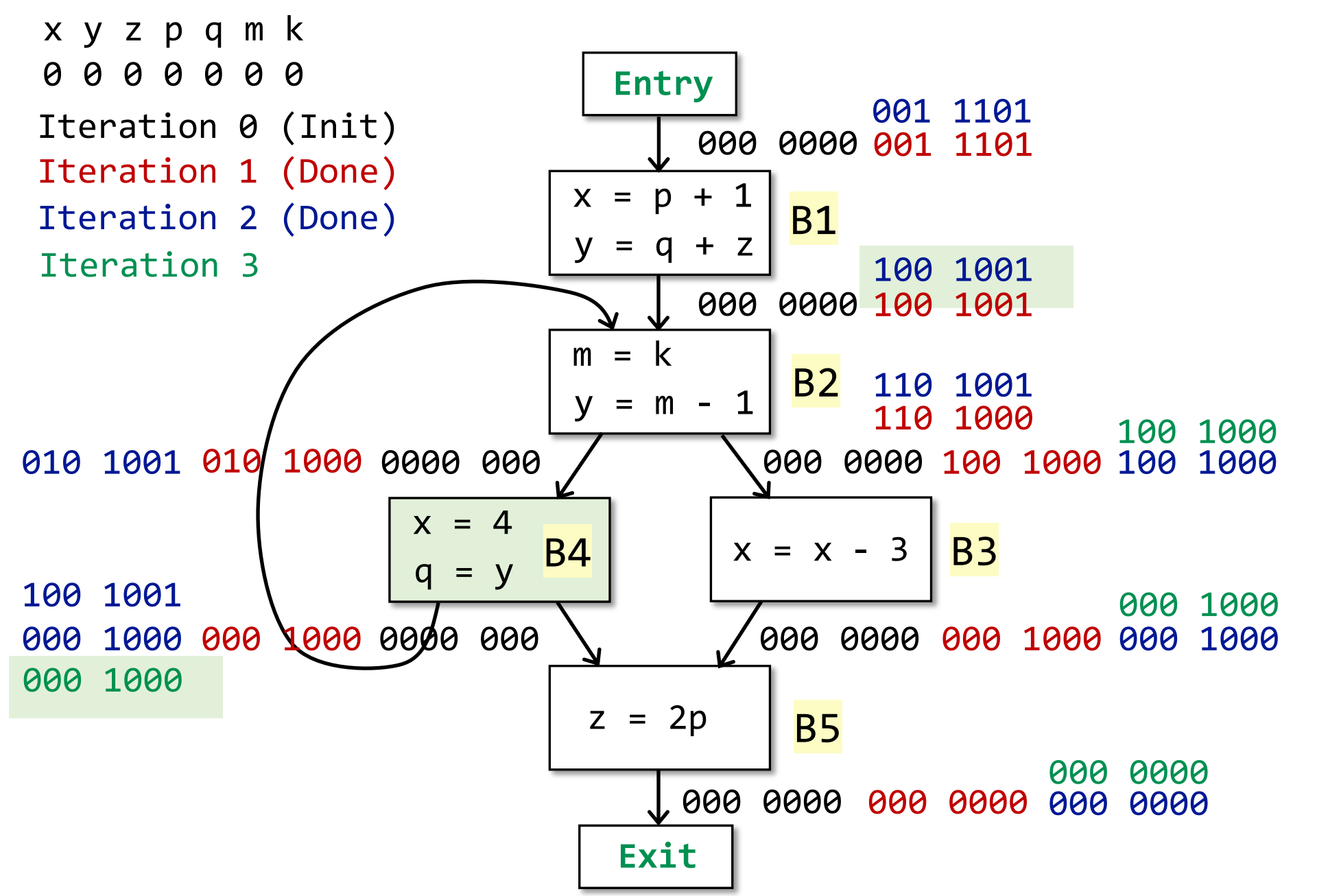

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000 000 0000 000 0000
Exit
Changes occur in
IN[] of B4

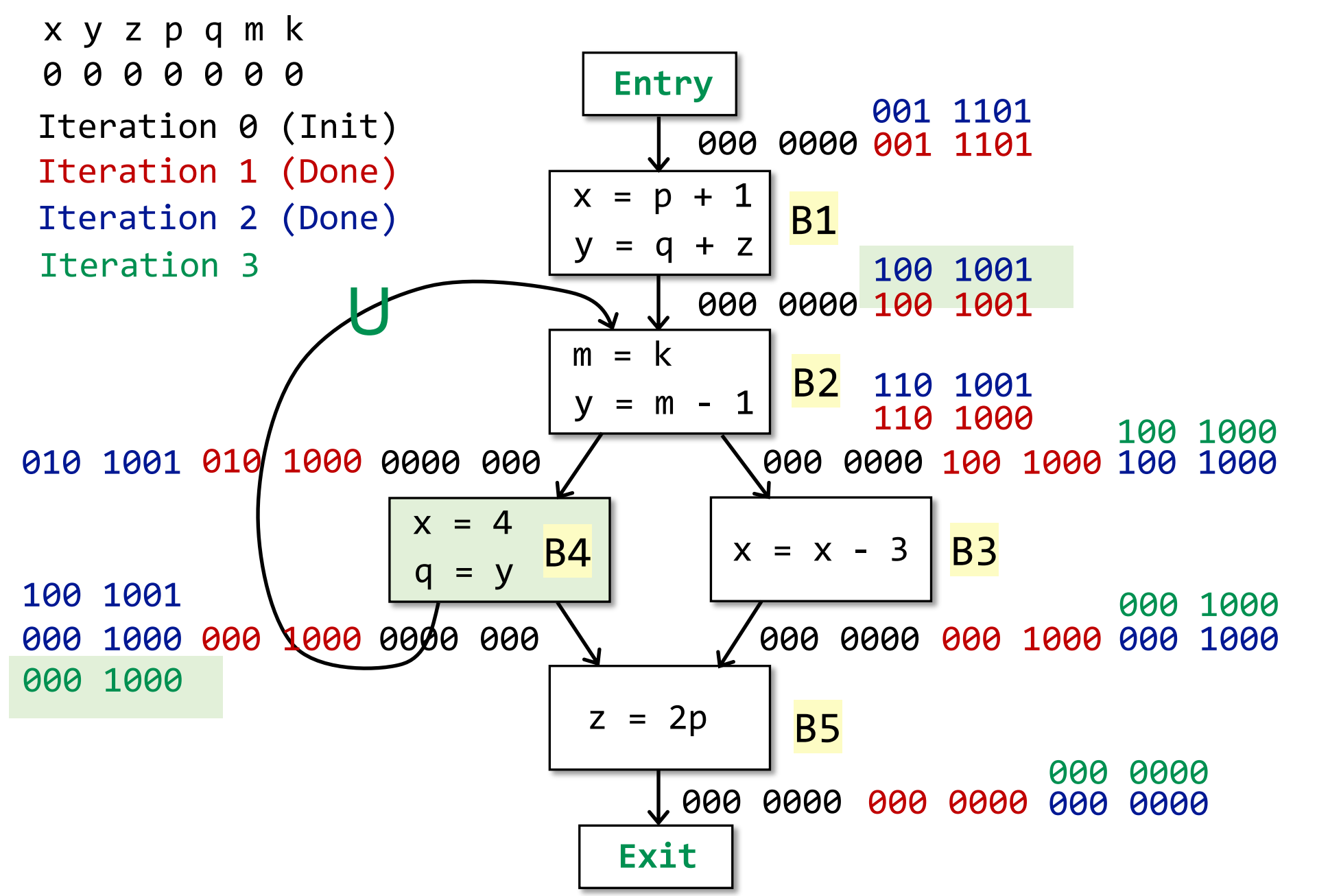

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit

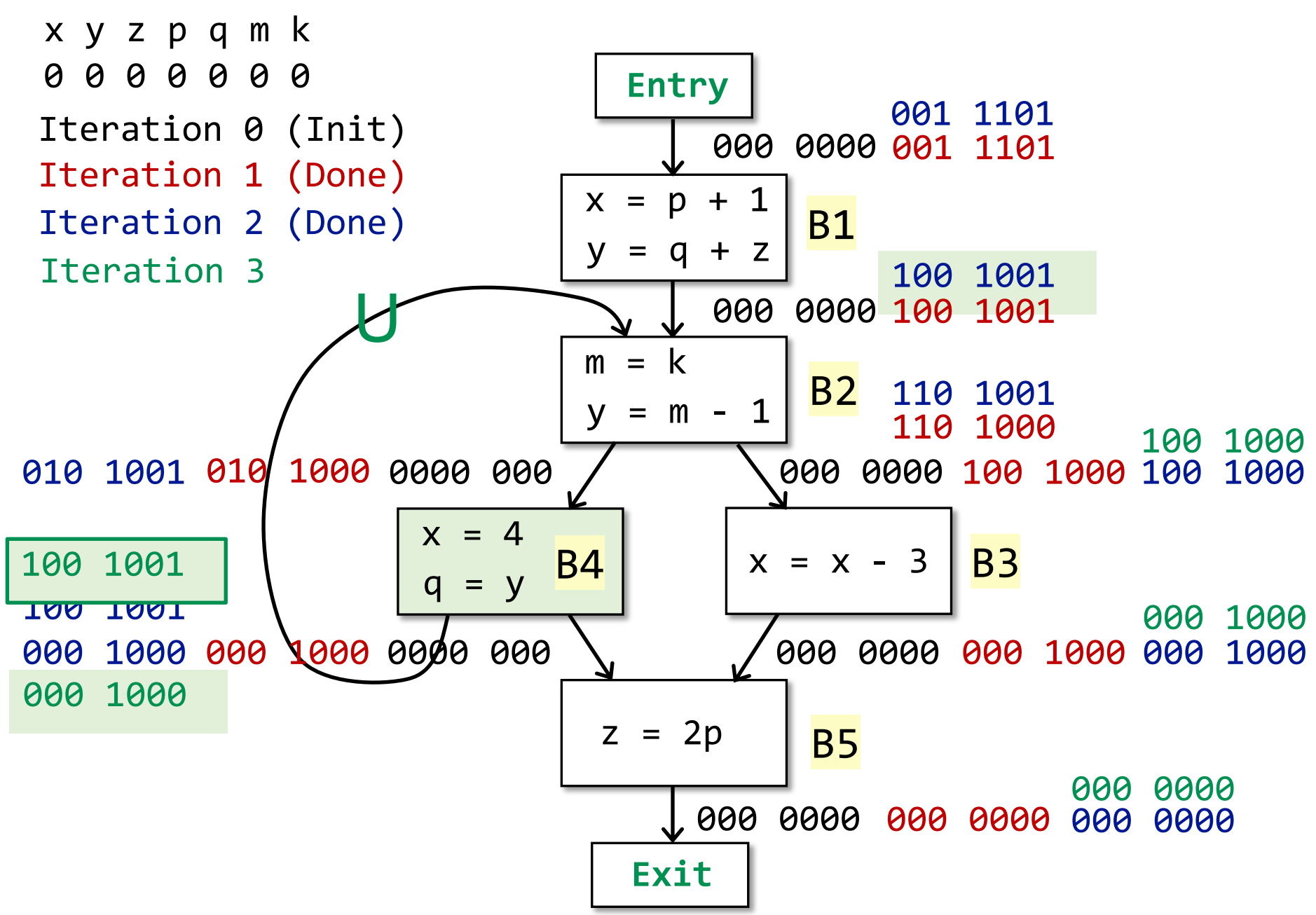

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000 000 1000 0000 000
000 1000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit

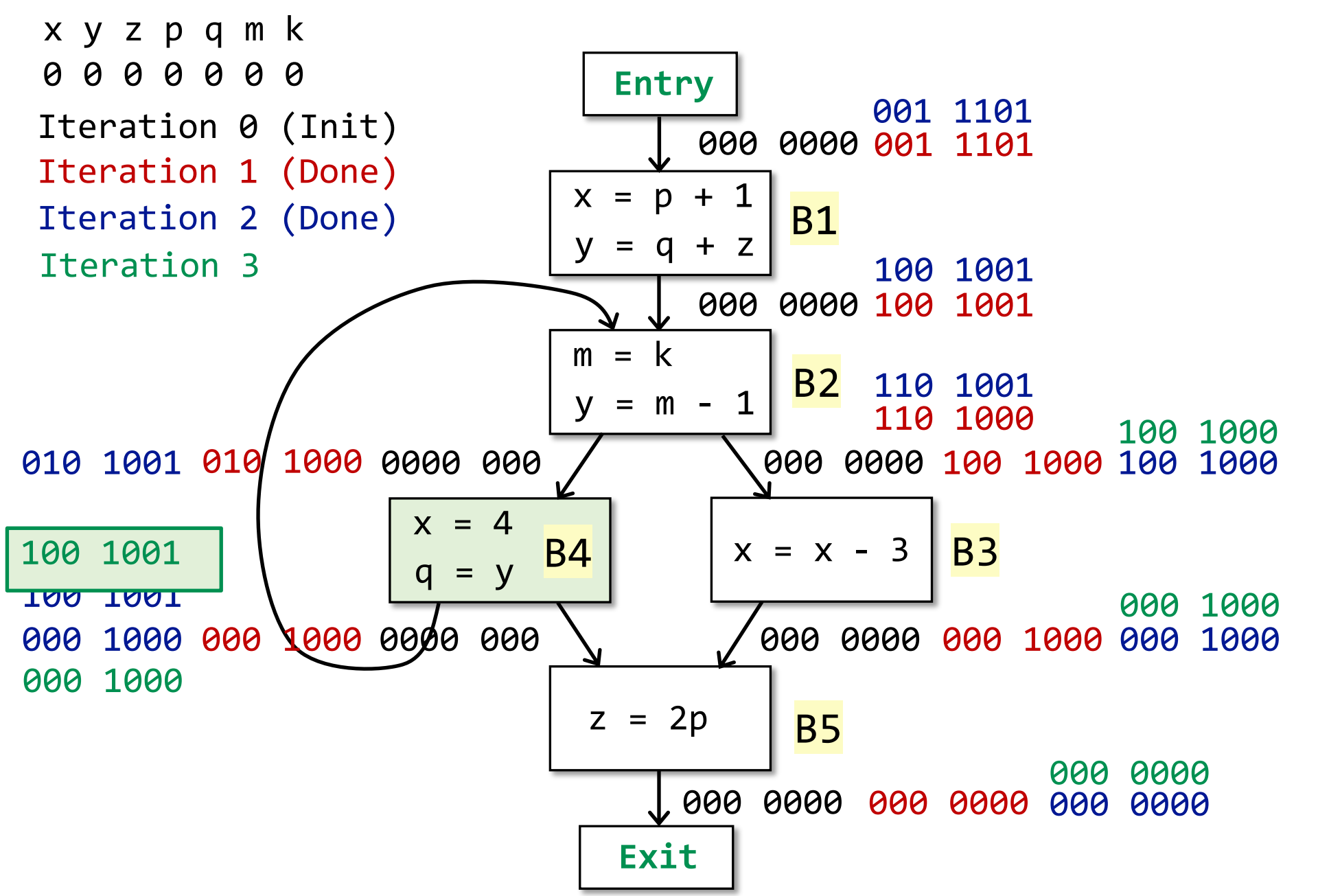

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit

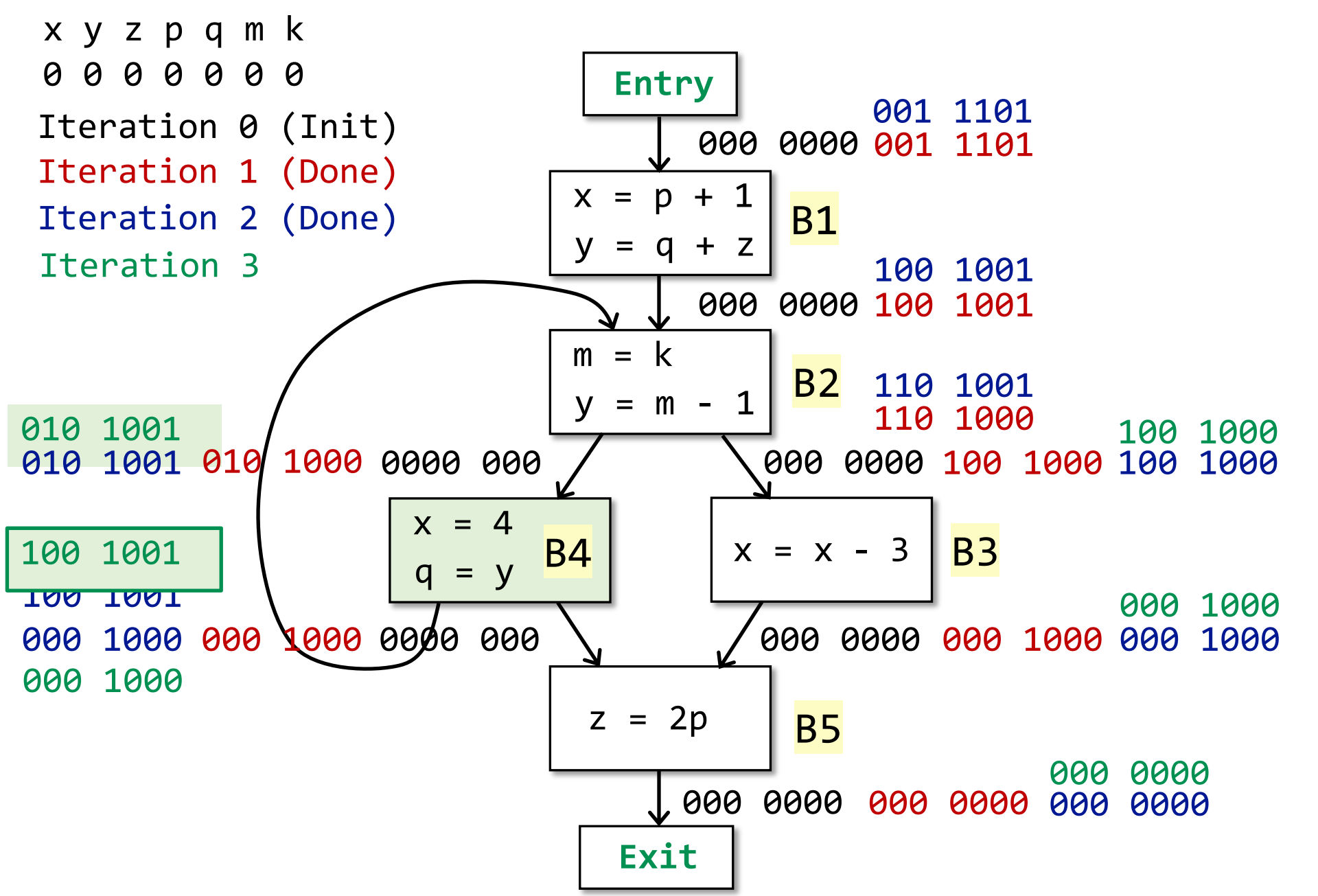

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
100 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit

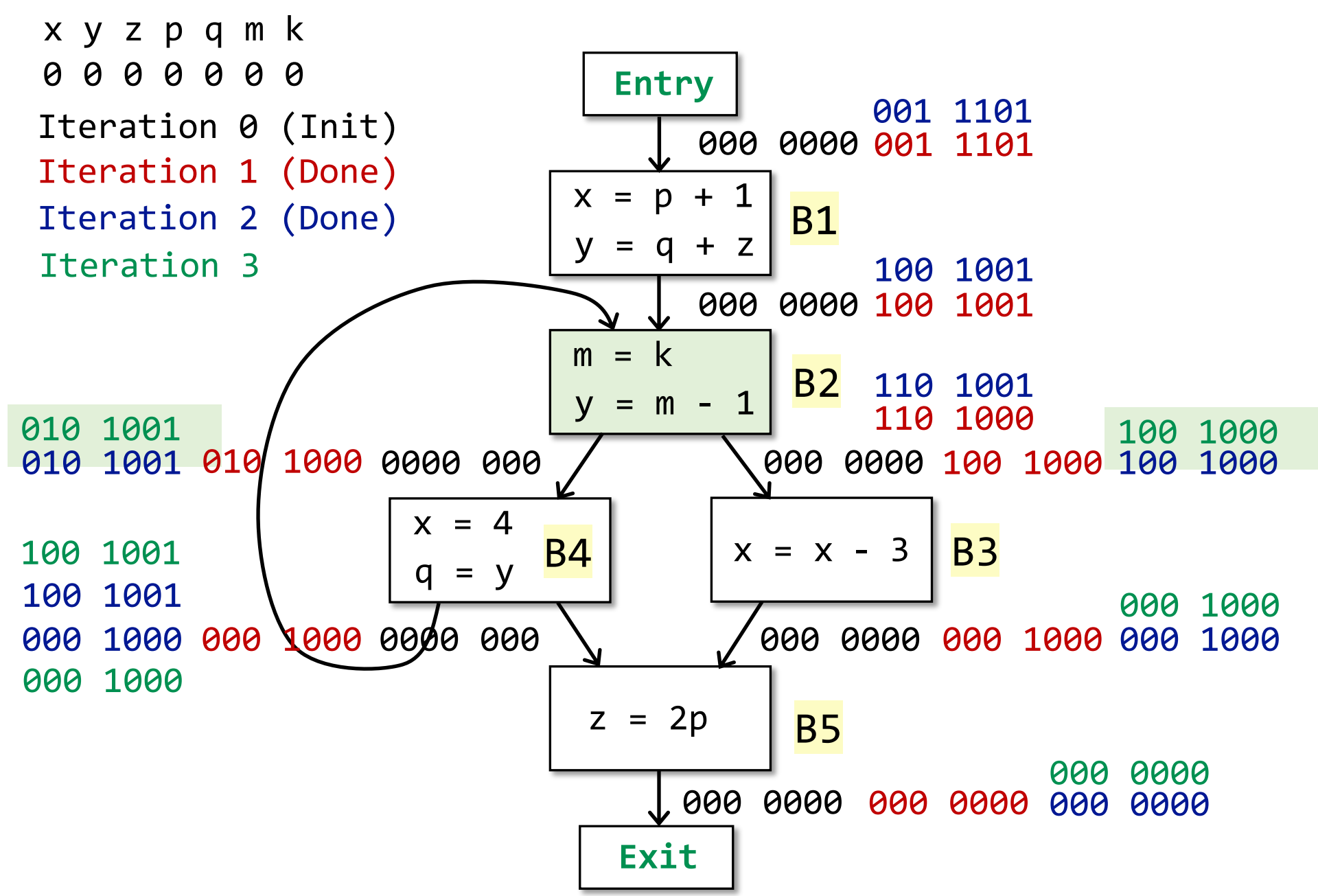

x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
100 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
100 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
100 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
100 1000
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
100 1000
010 1001
010 1001 010 1000 0000 000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Iteration 3
Entry
001 1101
000 0000 001 1101
x = p + 1
y = q + z
B1
100 1001
000 0000 100 1001
m = k
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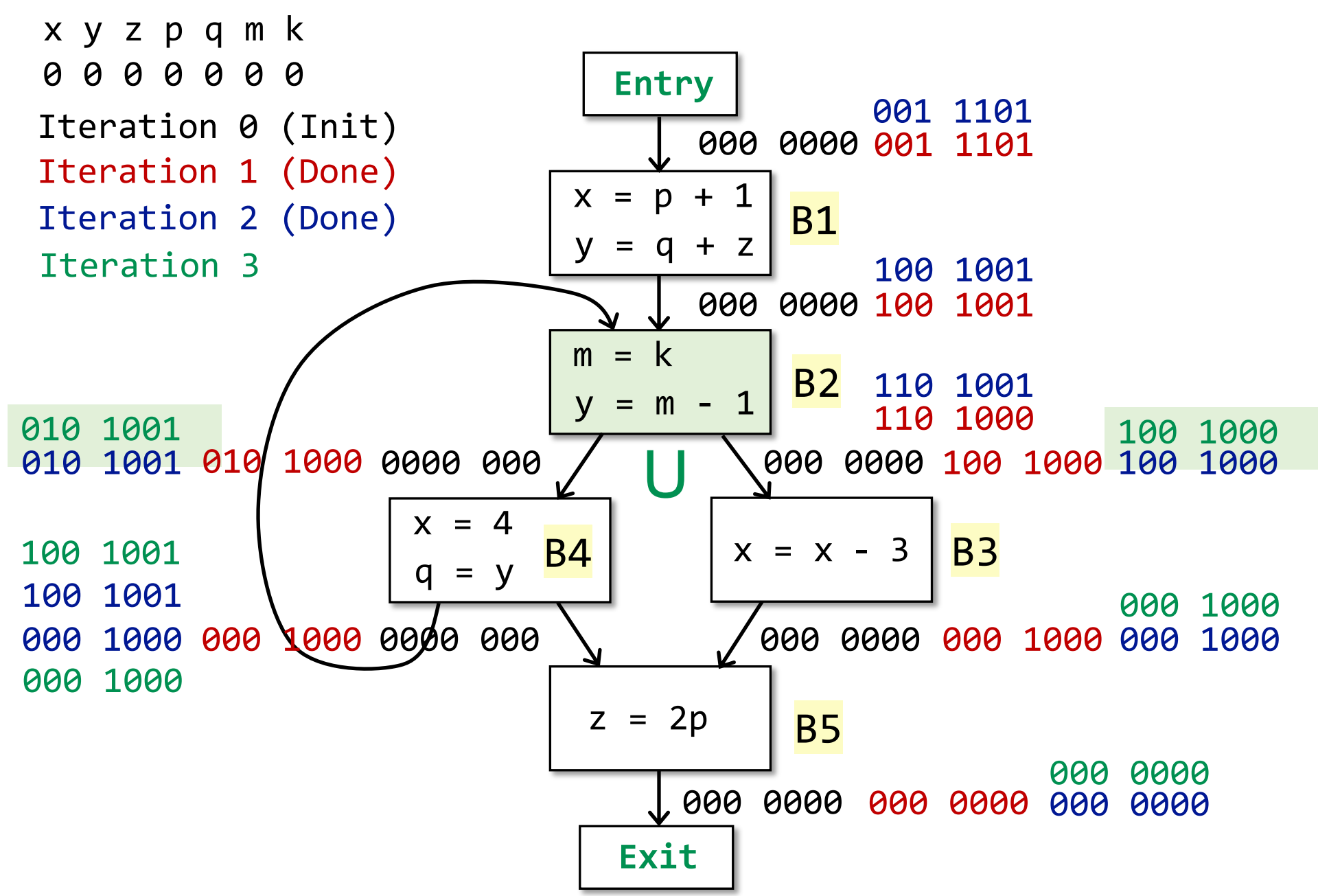
B2
110 1001
110 1000
010 1001
010 1001 010 1000 0000 000
000 0000 100 1000
100 1000
100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
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Iteration 0 (Init)
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000 0000 001 1101
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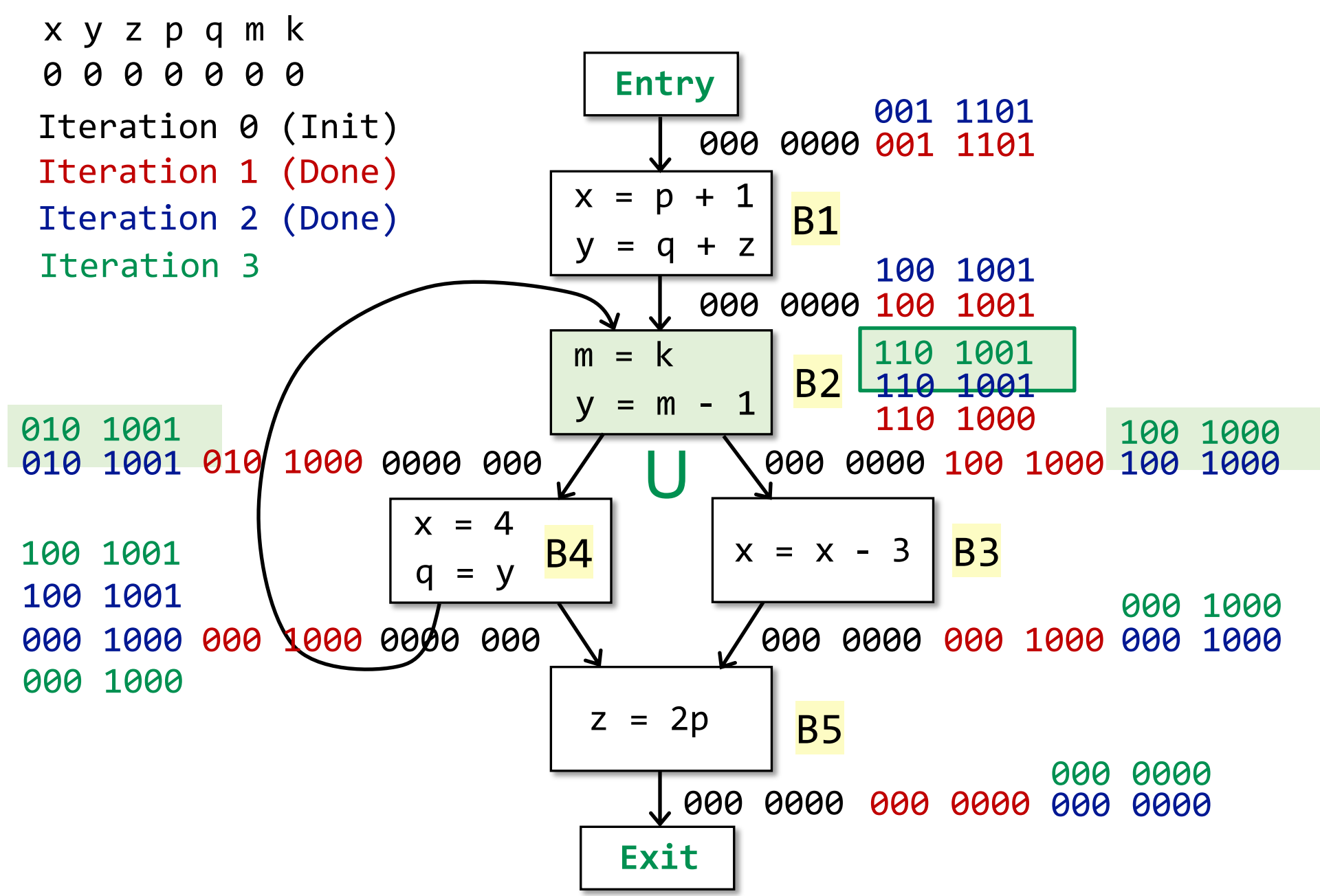
100 1001
000 0000 100 1001
m = k
y = m - 1
B2
110 1001
110 1000
010 1001
010 1001 010 1000 0000 000
U
000 0000 100 1000
100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
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Iteration 0 (Init)
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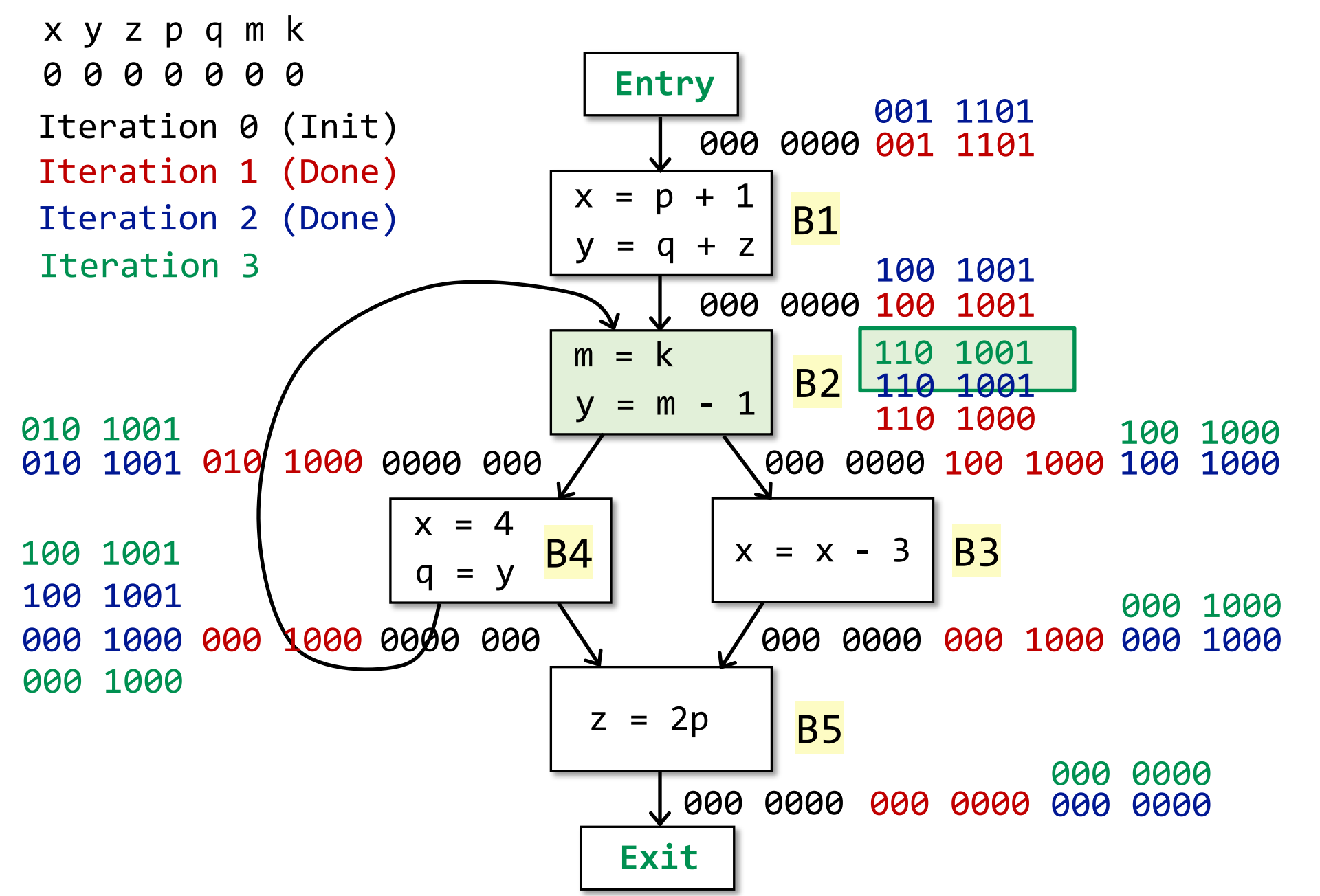
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000
000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
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001 1101
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010 1001
010 1001 010 1000 0000 000
100 1000
000 0000 100 1000 100 1000
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B4
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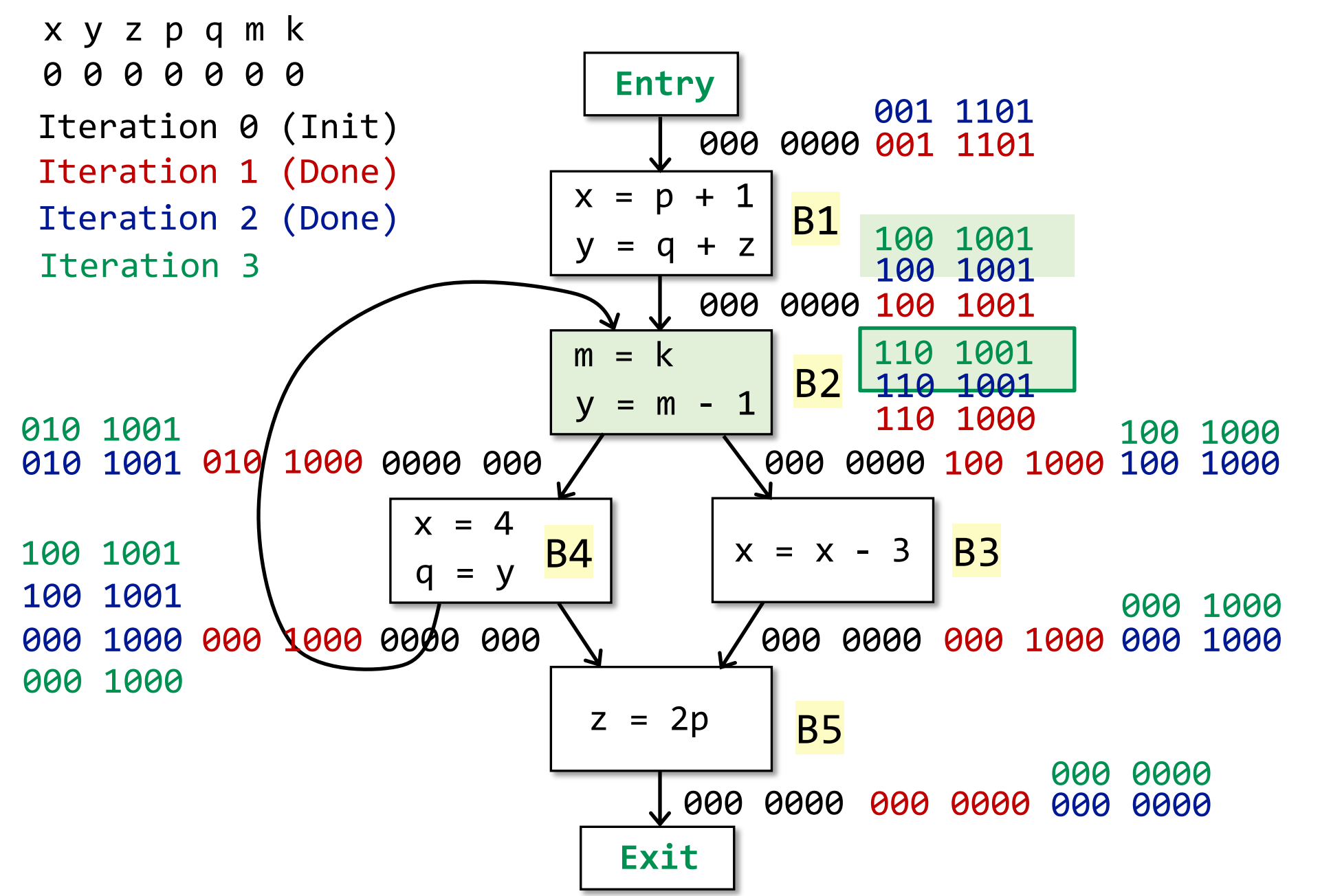
B3
100 1001
100 1001
000 1000 000 1000 0000 000
000 1000
000 1000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
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110 1001
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010 1001
010 1001 010 1000 0000 000
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000 0000 100 1000 100 1000
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000 1000 000 1000 0000 000
000 1000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
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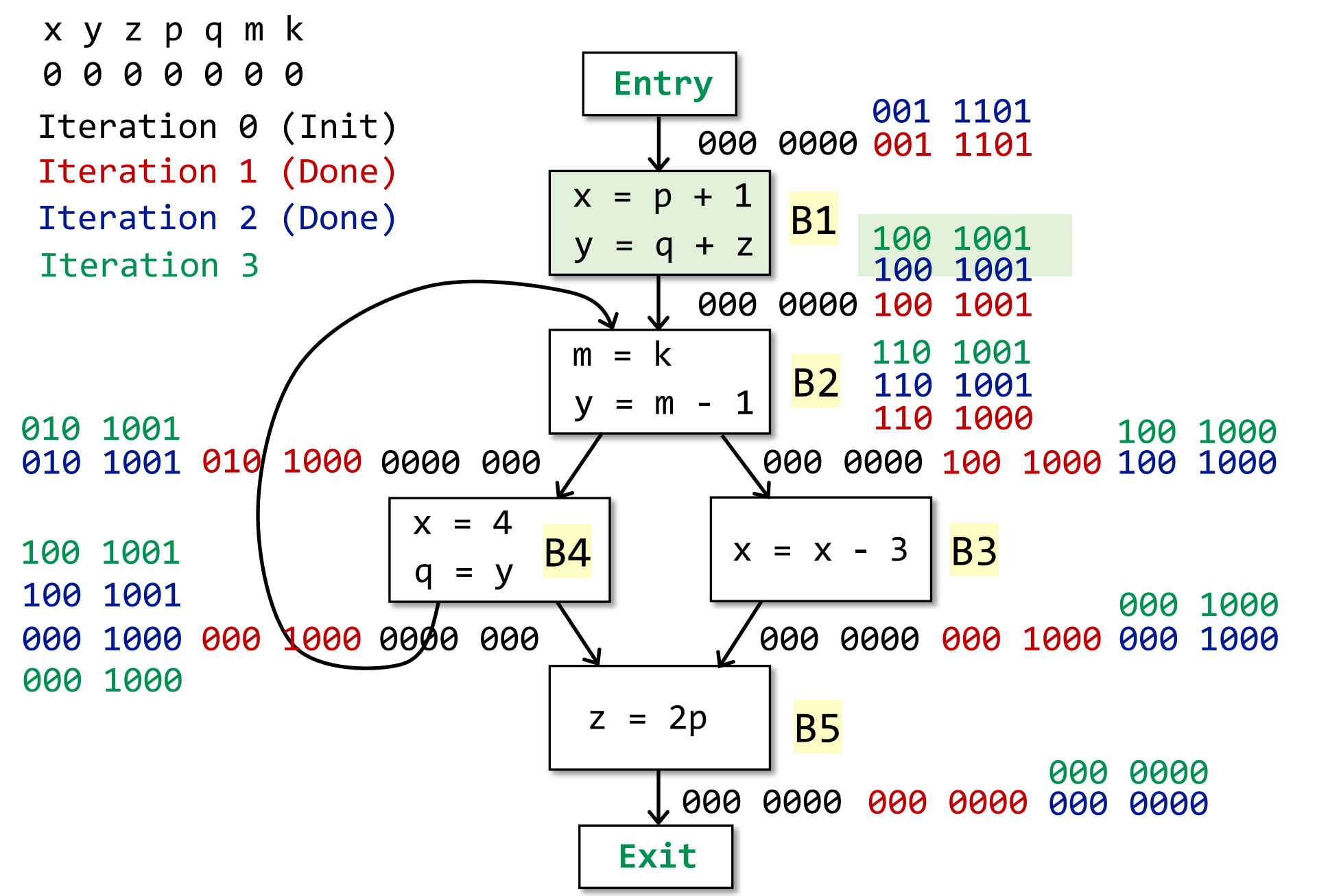
Exit


x y z p q m k
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Iteration 0 (Init)
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110 1001
110 1001
110 1000
010 1001
010 1001 010 1000 0000 000
100 1000
000 0000 100 1000 100 1000
x = 4
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B4
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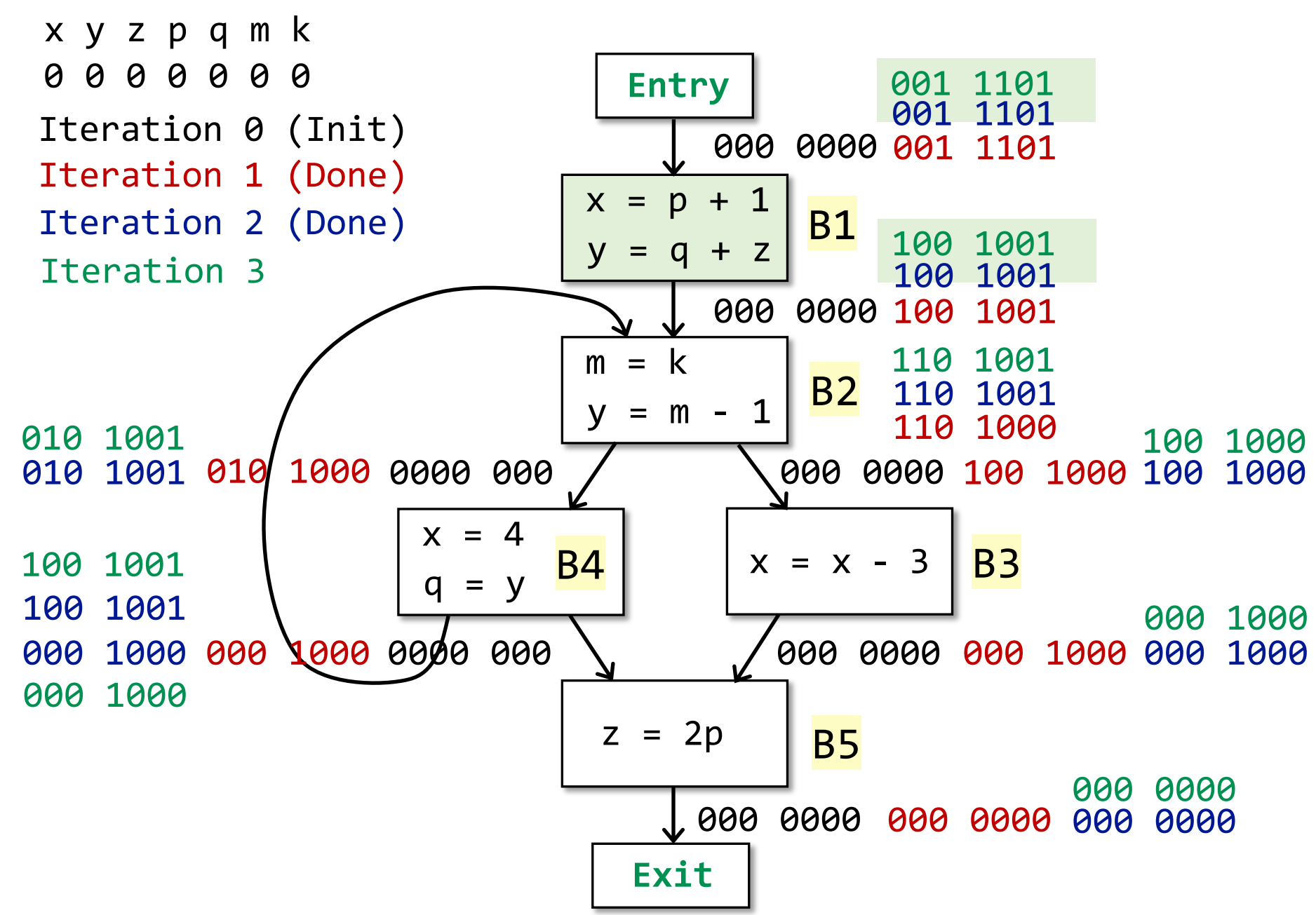
B3
100 1001
100 1001
000 1000
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
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Entry
001 1101
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110 1001
110 1000
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010 1001 010 1000 0000 000
100 1000
000 0000 100 1000 100 1000
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B3
100 1001
100 1001
000 1000 000 1000 0000 000
000 1000
000 0000 000 1000 000 1000
000 1000
z = 2p
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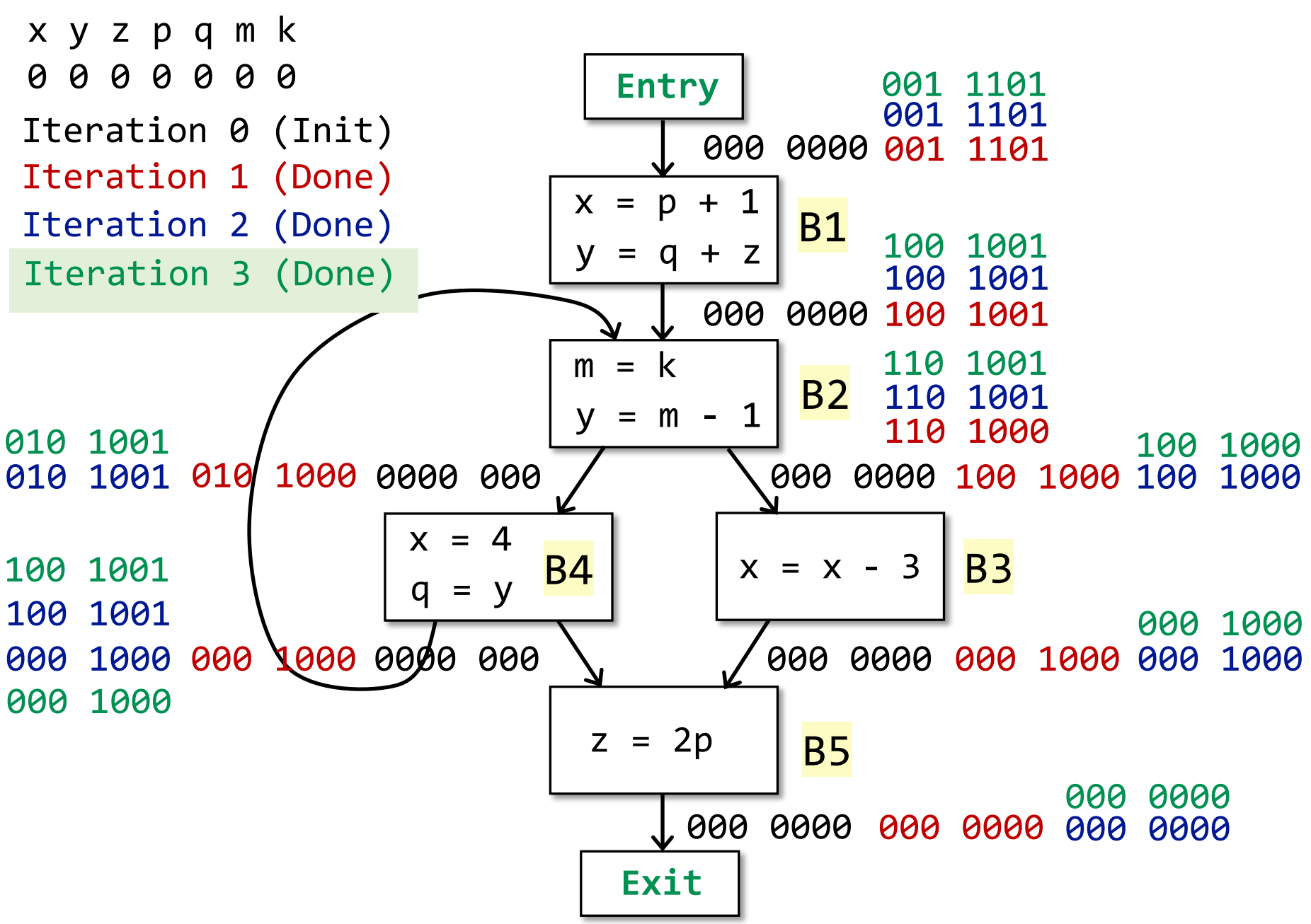
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
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100 1000
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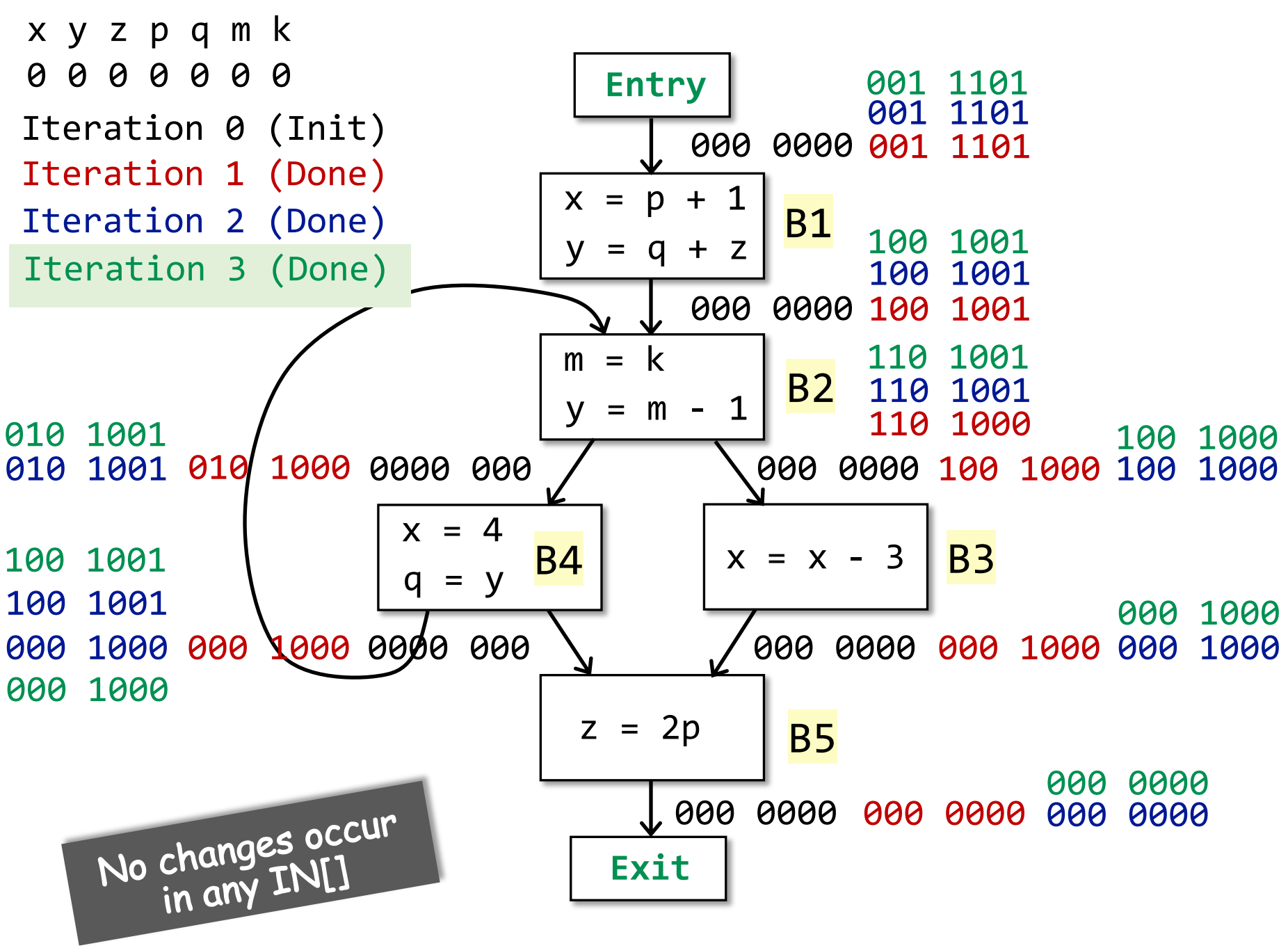
100 1001
100 1001
000 1000 000 1000 0000 000
000 1000
000 1000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
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Entry
001 1101
001 1101
000 0000 001 1101
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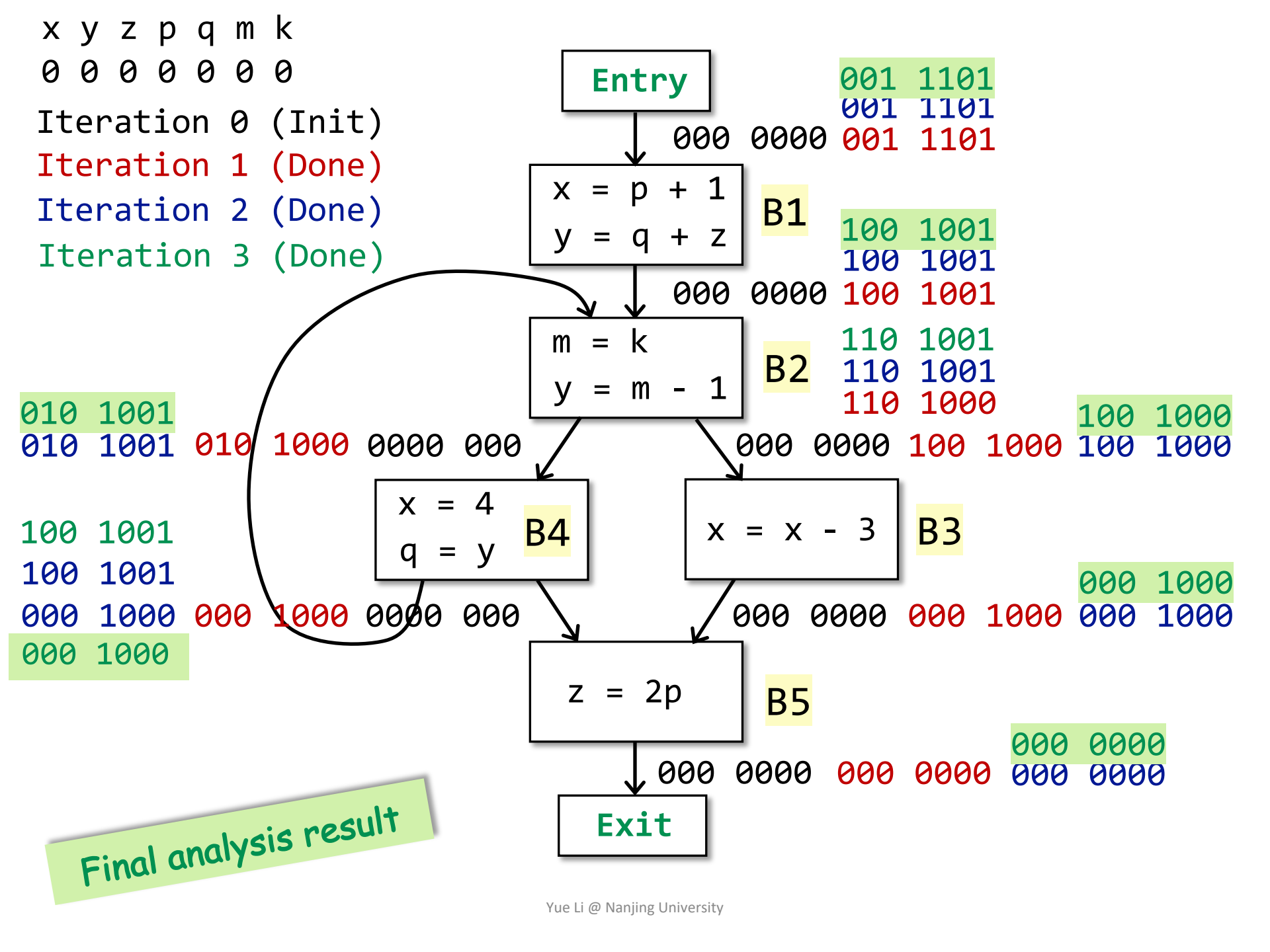
010 1001 010 1000 0000 000
100 1000
000 0000 100 1000 100 1000
x = 4
q = y
B4
x = x - 3
B3
100 1001
100 1001
000 1000 000 1000 0000 000
000 1000
000 1000
000 0000 000 1000 000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit
No changes occur in any IN[]


x y z p q m k
0 0 0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
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Iteration 3 (Done)
Entry
001 1101
001 1101
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x = p + 1
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000 0000 100 1000 100 1000
100 1000
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q = y
B4
x = x - 3
B3
100 1001
100 1001
000 1000 000 1000 0000 000
000 0000 000 1000 000 1000
000 1000
000 1000
z = 2p
B5
000 0000
000 0000 000 0000 000 0000
Exit
Final analysis result

Data Flow Analysis Applications

(I) Reaching Definitions Analysis

(II) Live Variables Analysis

(III) Available Expressions Analysis

Available Expressions Analysis

An expression x *op* y is available at program point p if (1) **all** paths from the entry to p **must** pass through the evaluation of x *op* y, and (2) after the last evaluation of x *op* y, there is no redefinition of x or y

Available Expressions Analysis

An expression x *op* y is available at program point p if (1) **all** paths from the entry to p **must** pass through the evaluation of x *op* y, and (2) after the last evaluation of x *op* y, there is no redefinition of x or y

- This definition means at program p, we can replace expression x *op* y by the result of its last evaluation
- The information of available expressions can be used for detecting global common subexpressions.

Understanding Available Expressions Analysis

Abstraction

- Data Flow Values/Facts
  - All the expressions in a program
  - Can be represented by bit vectors

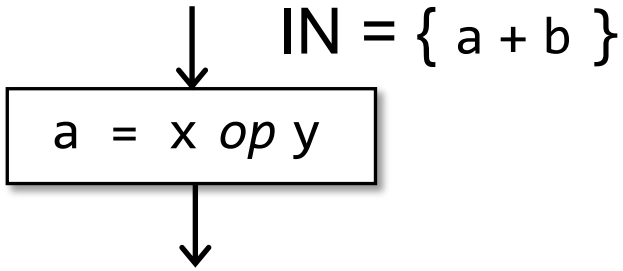
e.g., E1, E2, E3, E4, …, E100 (100 expressions)

00000…0

100 bits

Bit i from the left represents expression Ei

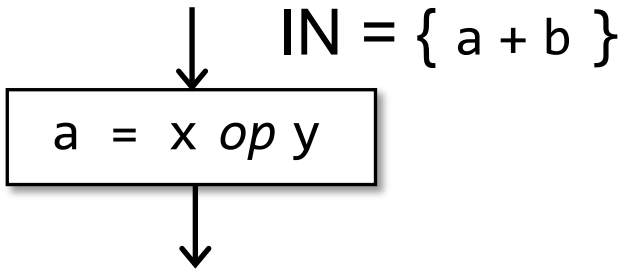
Understanding Available Expressions Analysis



Safe-approximation

Understanding Available Expressions Analysis

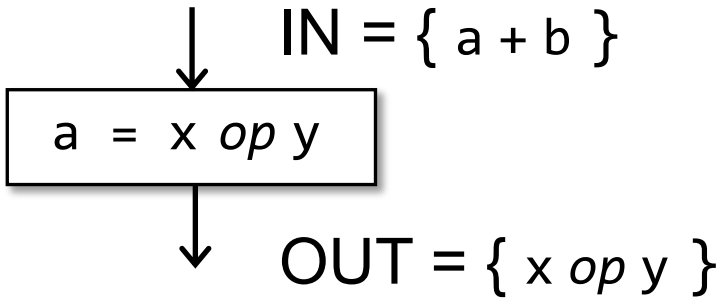
Safe-approximation



- Add to OUT the expression x *op* y (gen)
- Delete from IN any expression involving variable a (kill)

Understanding Available Expressions Analysis

Safe-approximation



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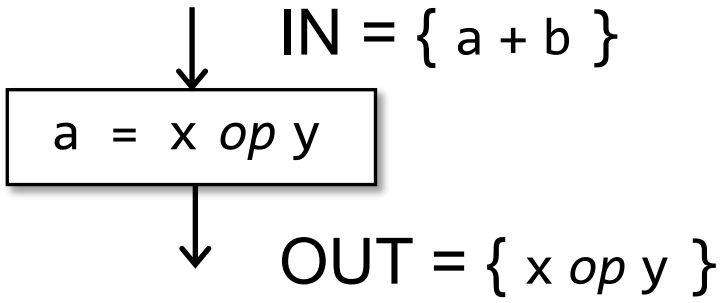
Understanding Available Expressions Analysis

Safe-approximation



- Add to OUT the expression x *op* y (gen)
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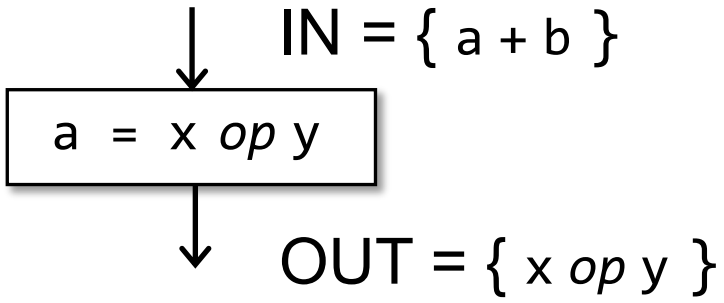
$$OUT[B] = gen_B \cup (IN[B] - kill_B)$$

Understanding Available Expressions Analysis

Safe-approximation



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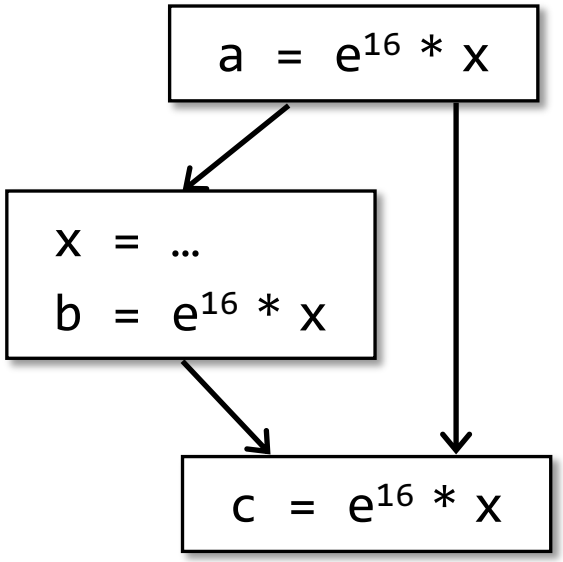
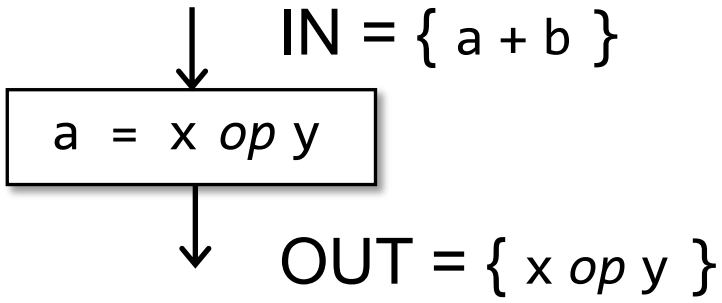


Understanding Available Expressions Analysis

Safe-approximation



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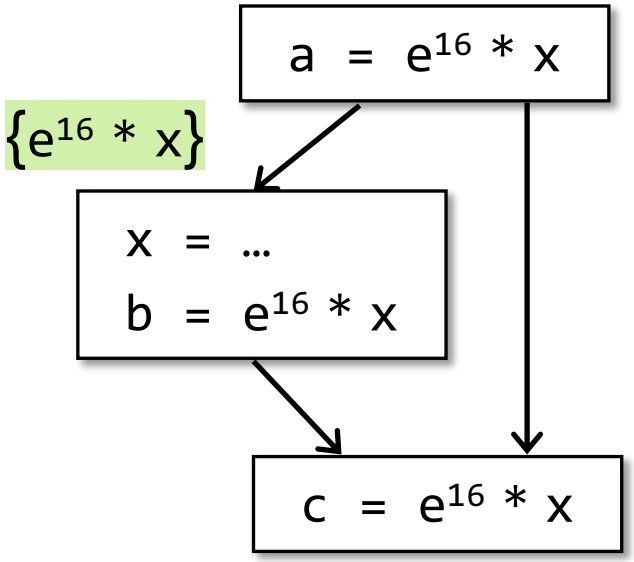
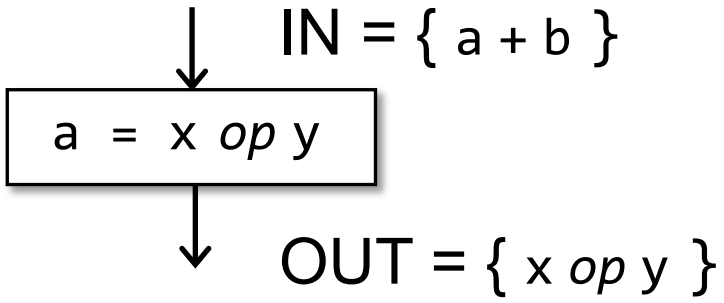


Understanding Available Expressions Analysis

Safe-approximation



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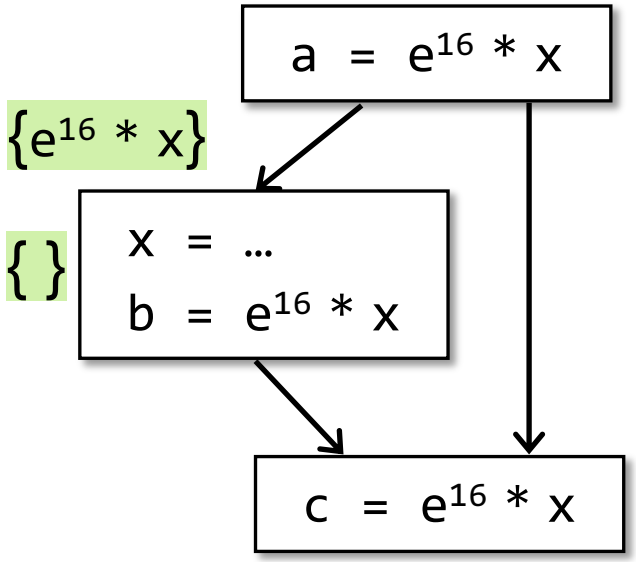
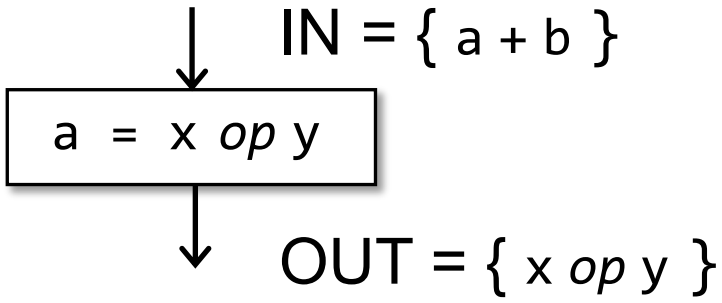


Understanding Available Expressions Analysis

Safe-approximation



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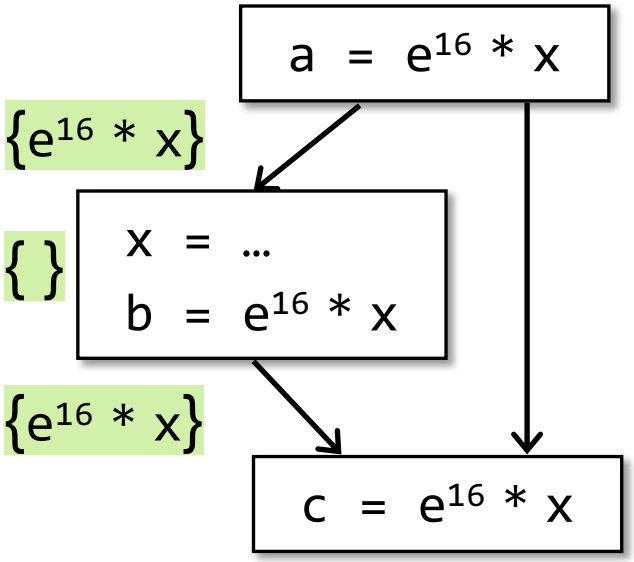
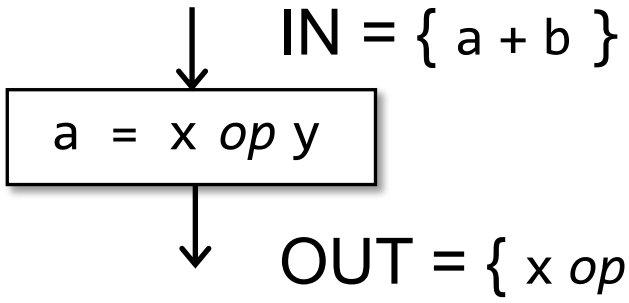


Understanding Available Expressions Analysis

Safe-approximation



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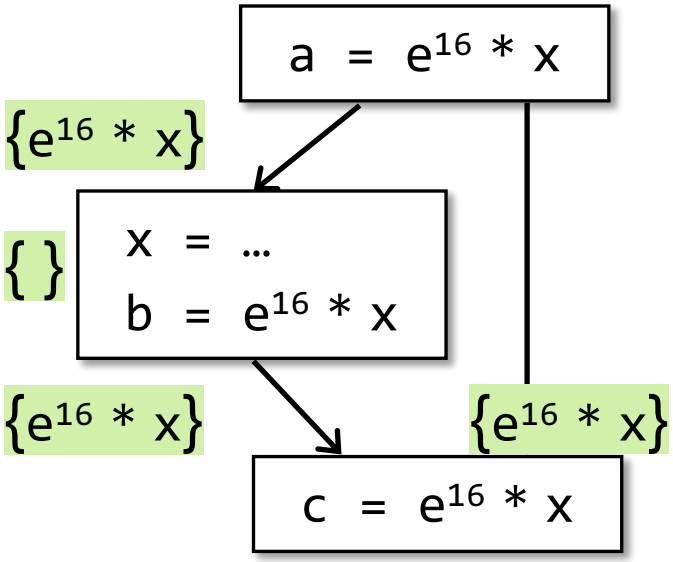
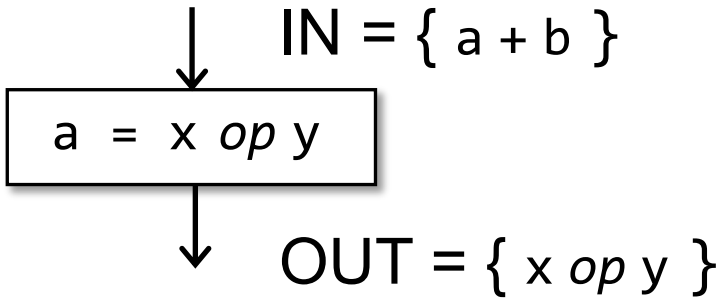


Understanding Available Expressions Analysis

Safe-approximation



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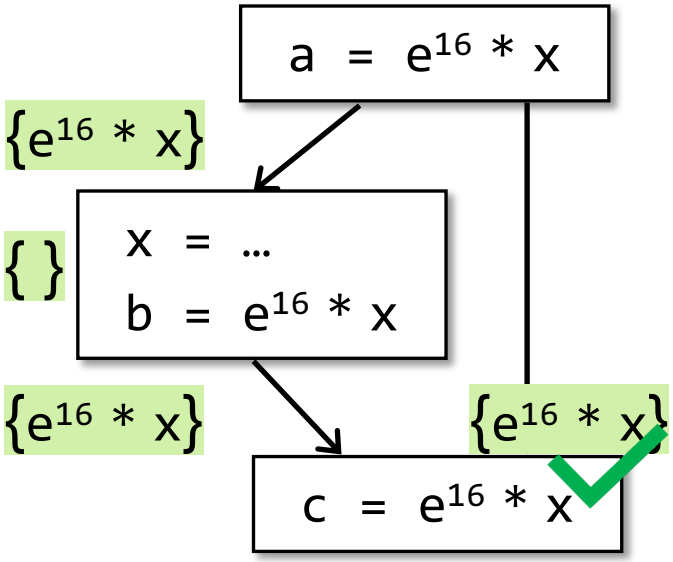
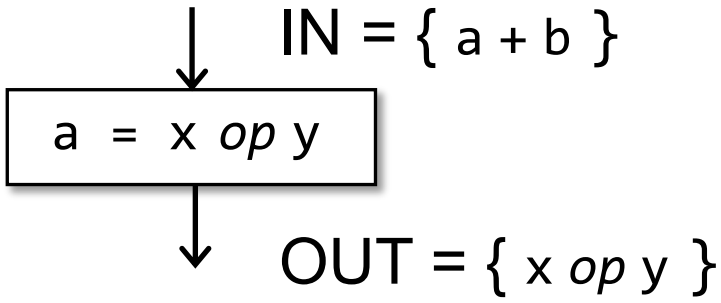


Understanding Available Expressions Analysis

Safe-approximation



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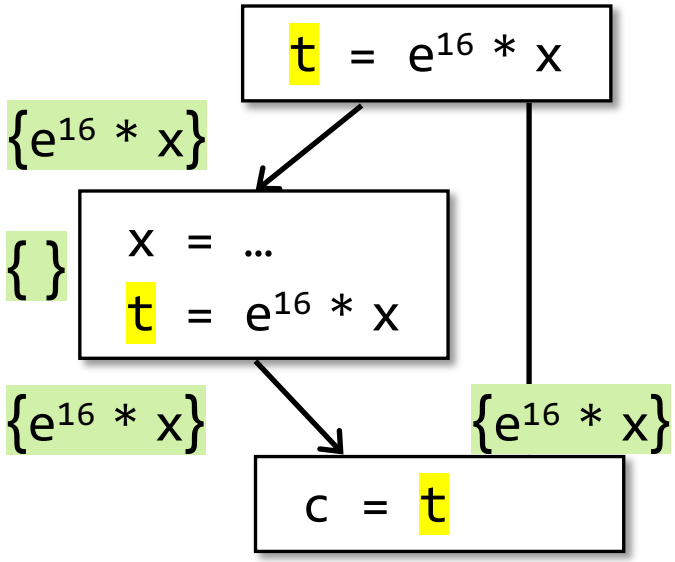
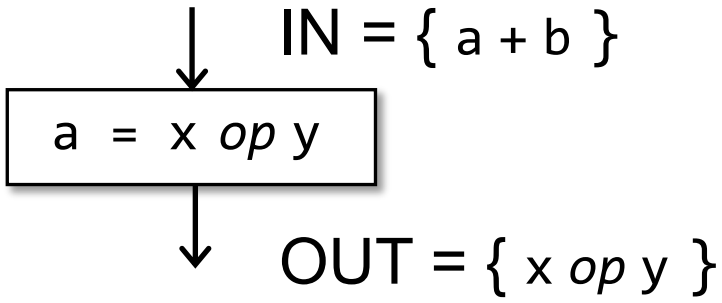


Understanding Available Expressions Analysis

Safe-approximation



- Add to OUT the expression x *op* y (gen)
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$$OUT[B] = gen_B \cup (IN[B] - kill_B)$$

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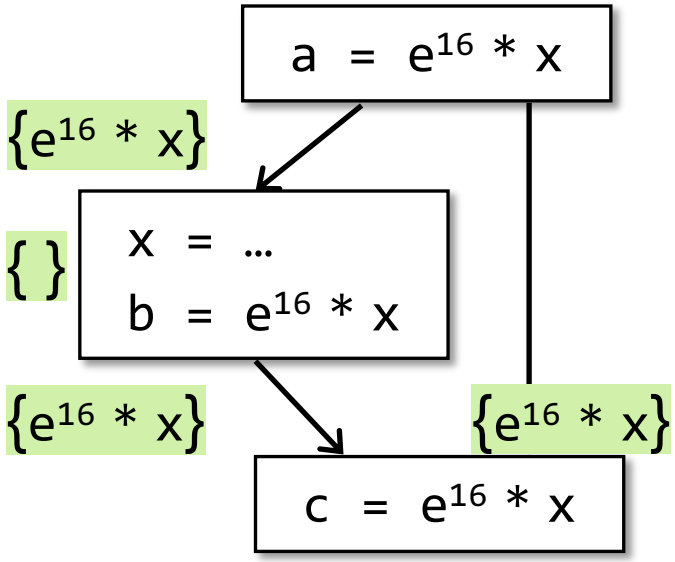
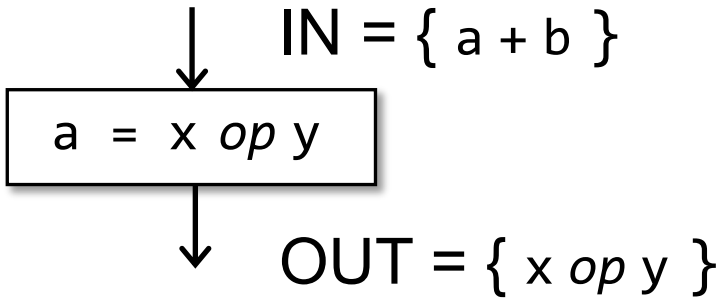


Understanding Available Expressions Analysis

Safe-approximation



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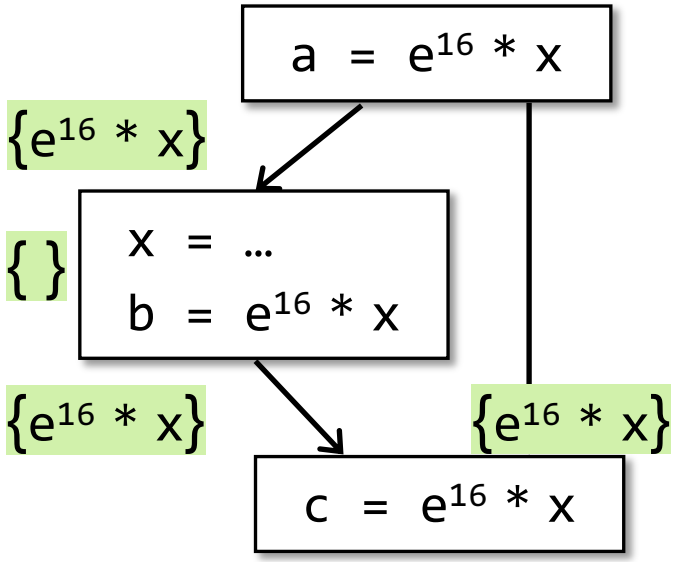
All paths from entry to point p must pass through the evaluation of x *op* y



Understanding Available Expressions Analysis

Safe-approximation

IN = { a + b }

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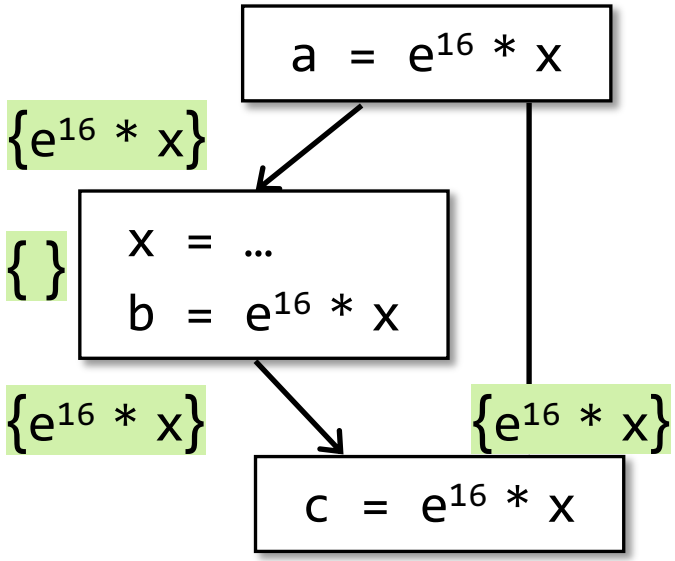

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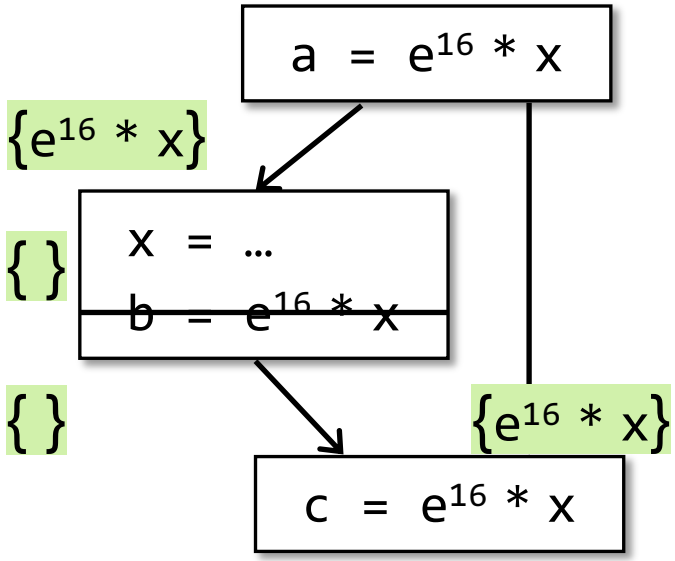

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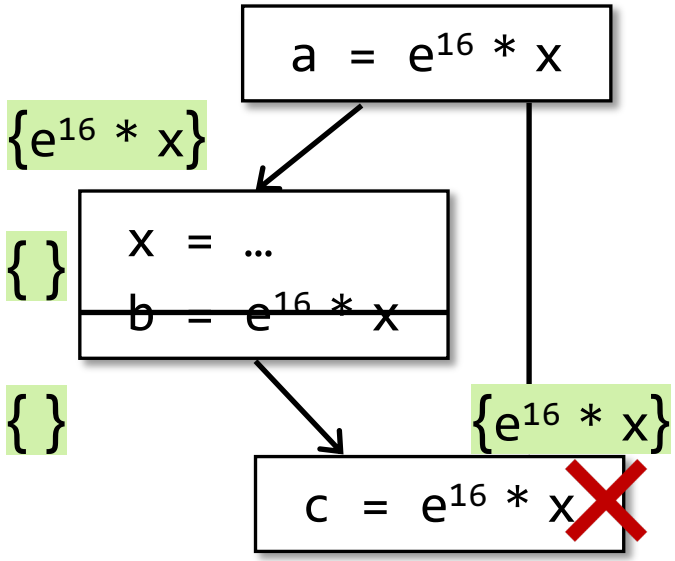

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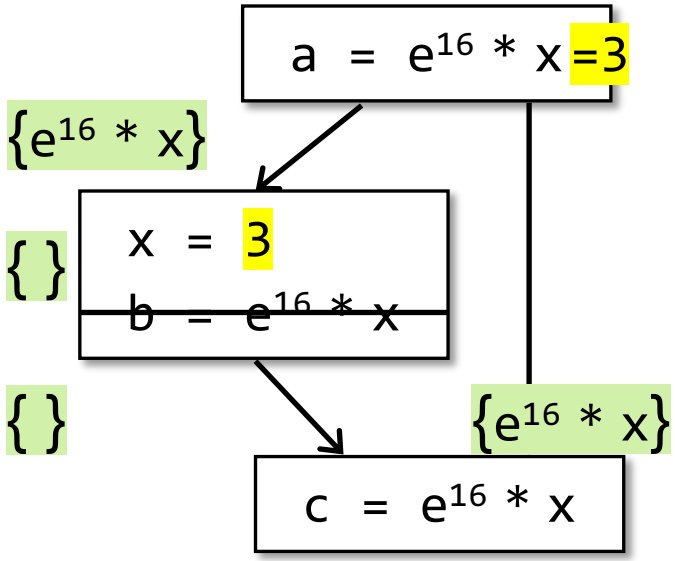

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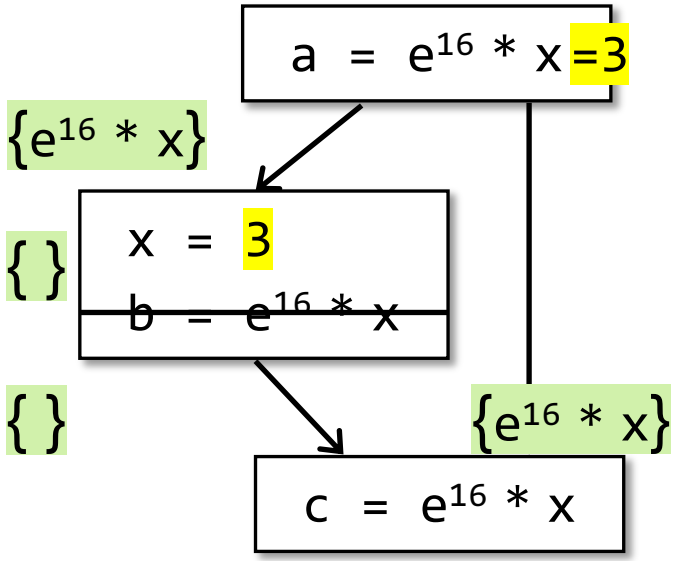

Algorithm of Available Expressions Analysis

INPUT: CFG ($kill_B$ and gen_B computed for each basic block B)

OUTPUT: IN[B] and OUT[B] for each basic block B

METHOD:

OUT[*entry*] = ∅;
for (each basic block *B**entry*)
    OUT[*B*] = U;
while (changes to any OUT occur)
    for (each basic block *B**entry*) {
        IN[*B*] = $\bigcap_{P \text{ a predecessor of } B}$ OUT[*P*];
        OUT[*B*] = gen_B U (IN[*B*] - $kill_B$);
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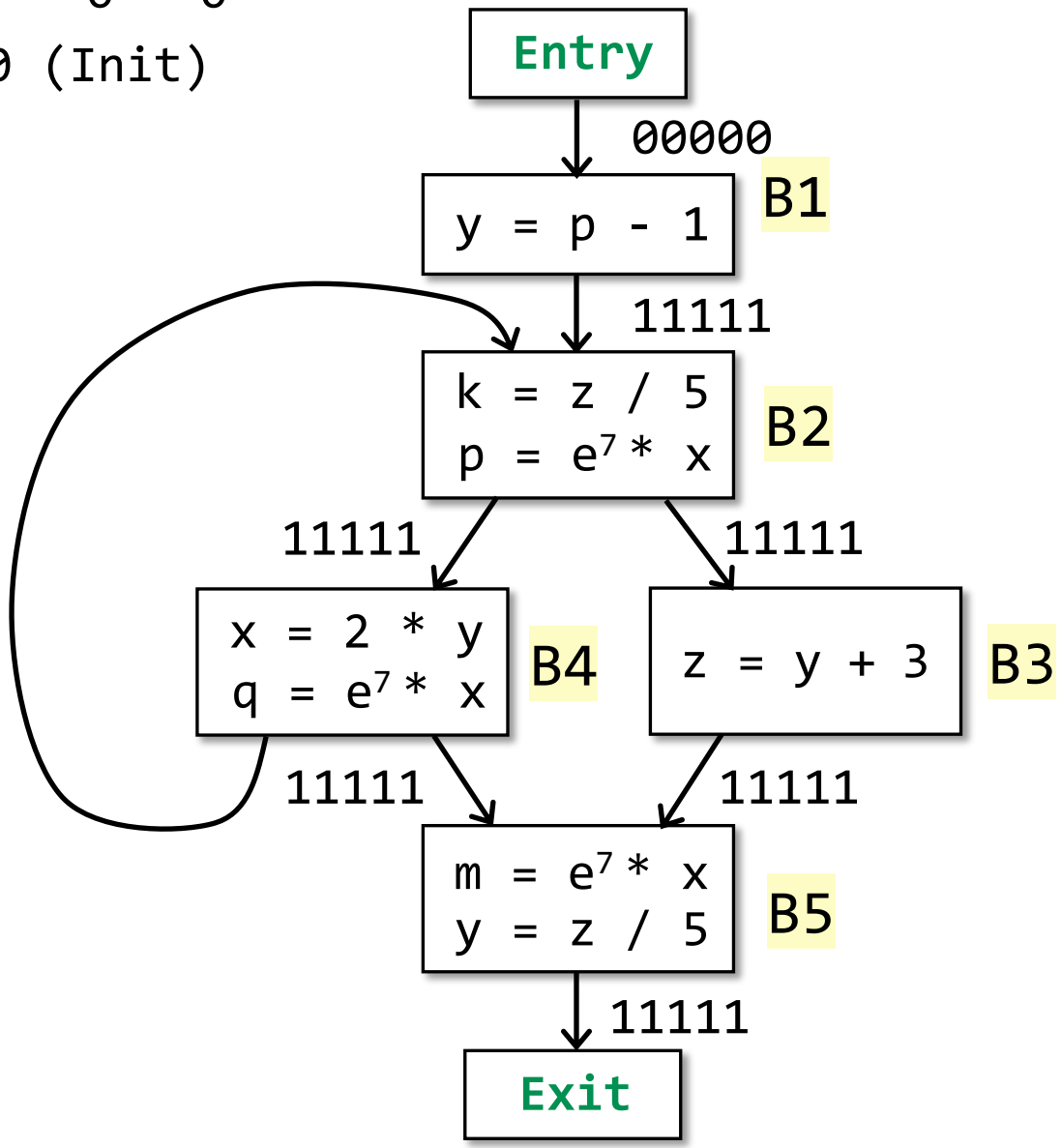
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

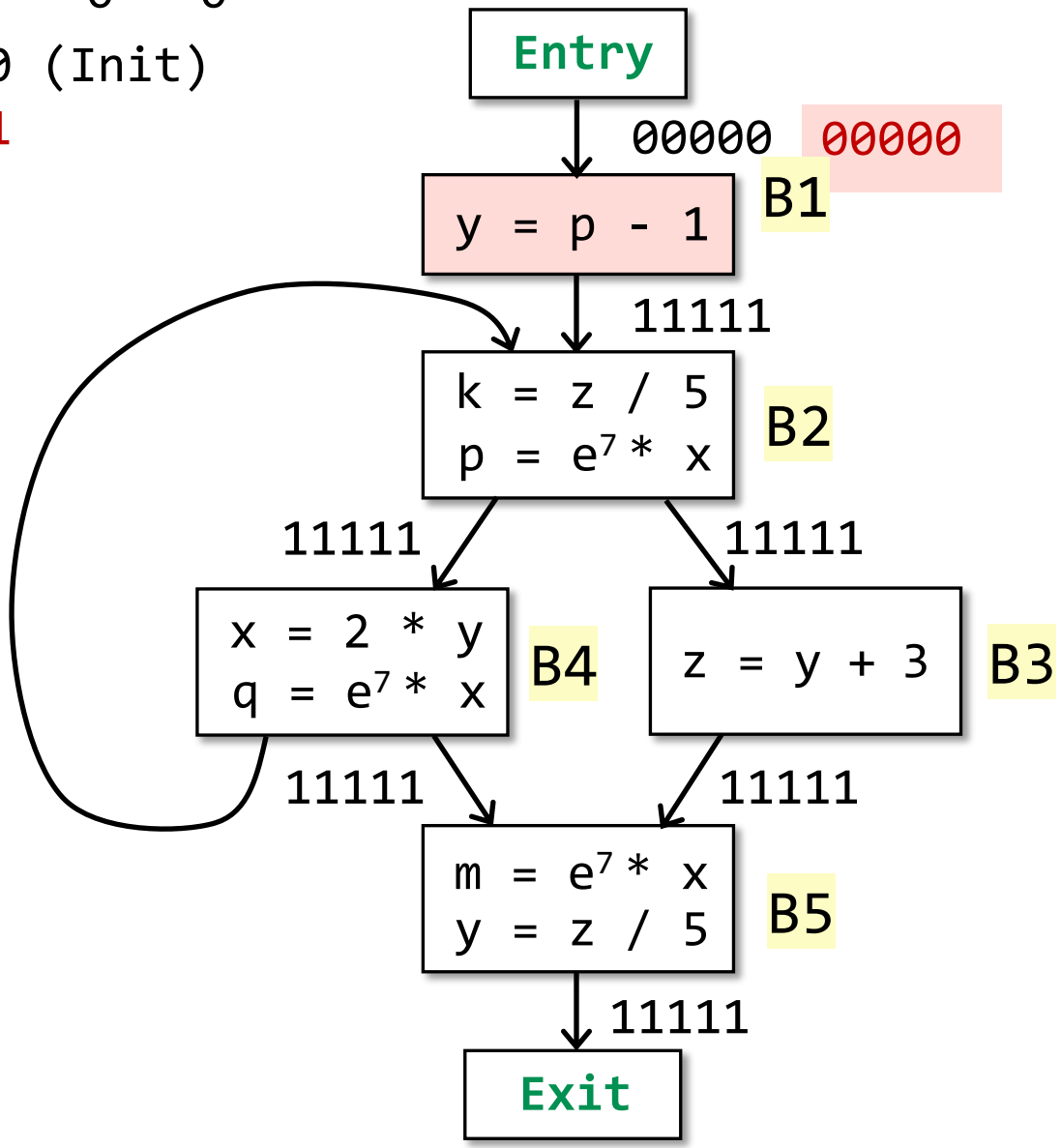


p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1

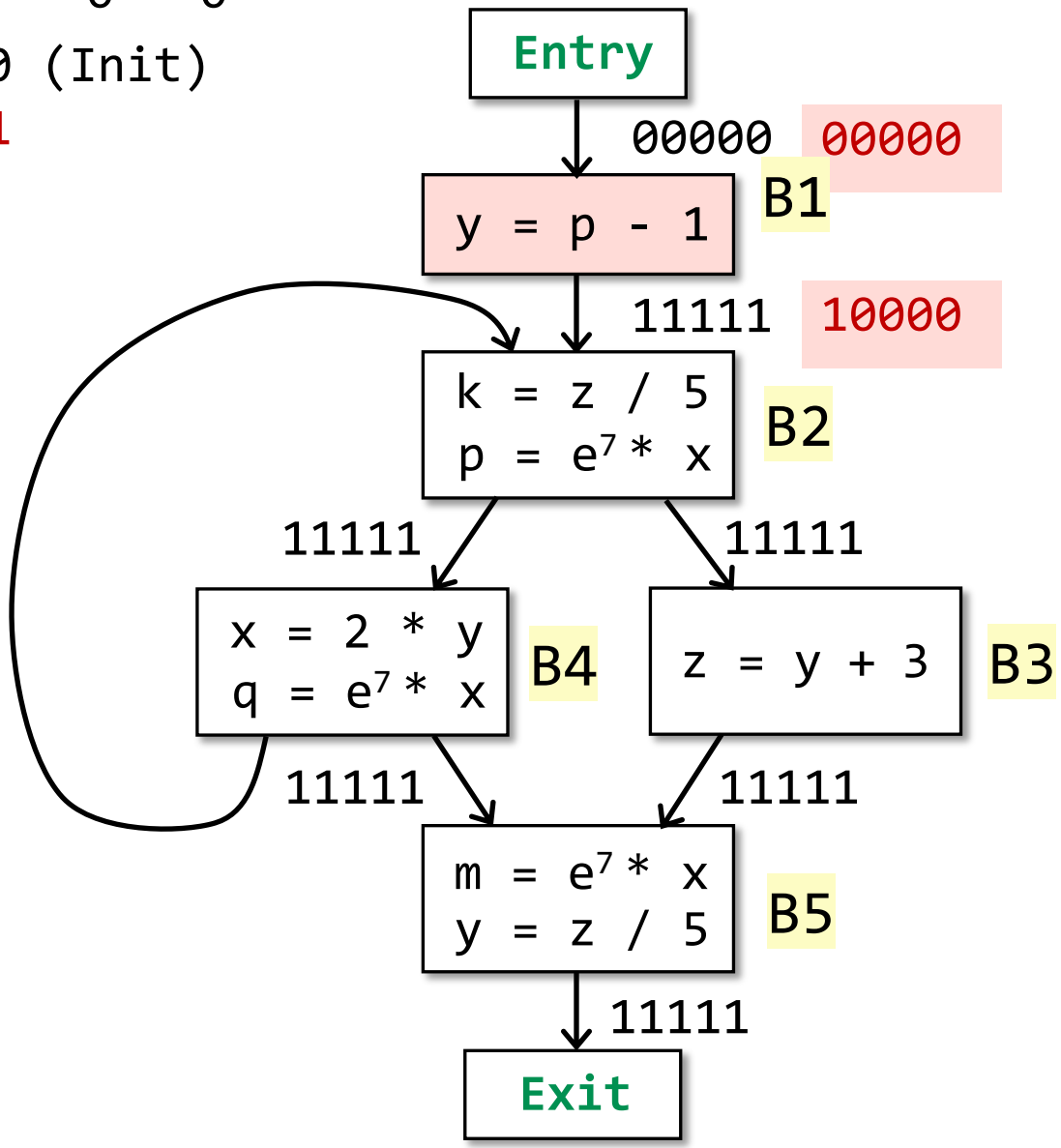


p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1



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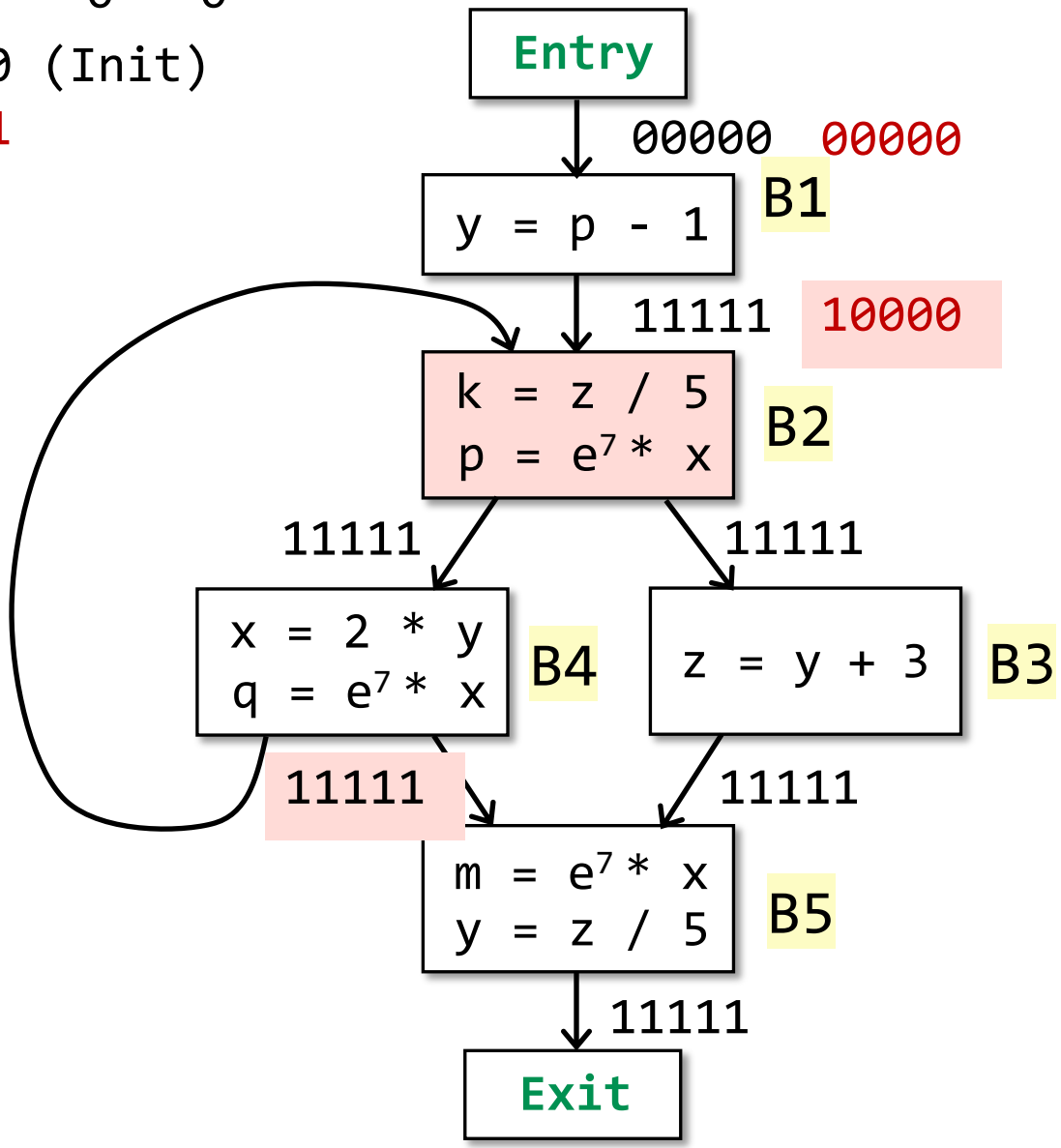

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Iteration 0 (Init)

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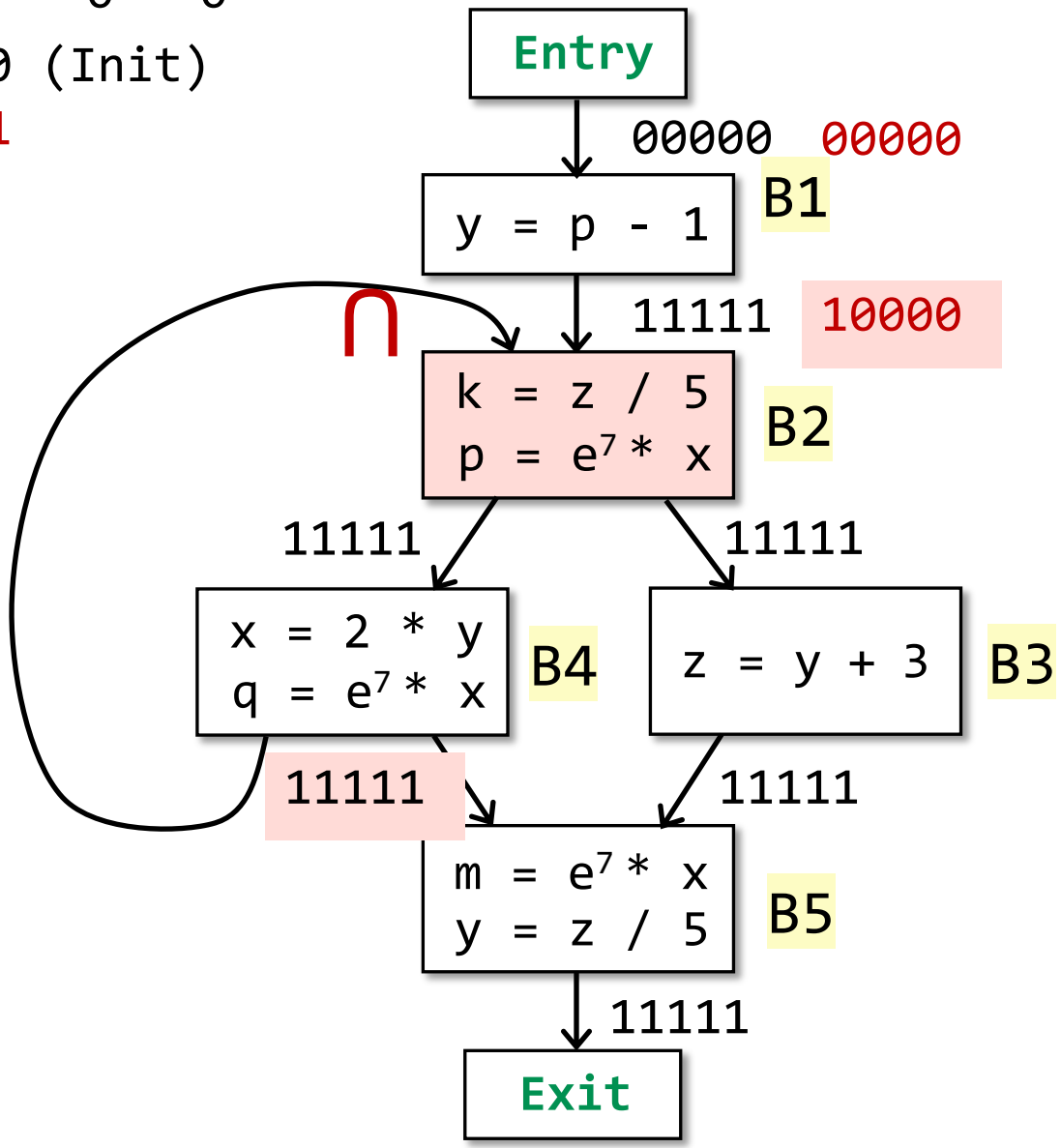

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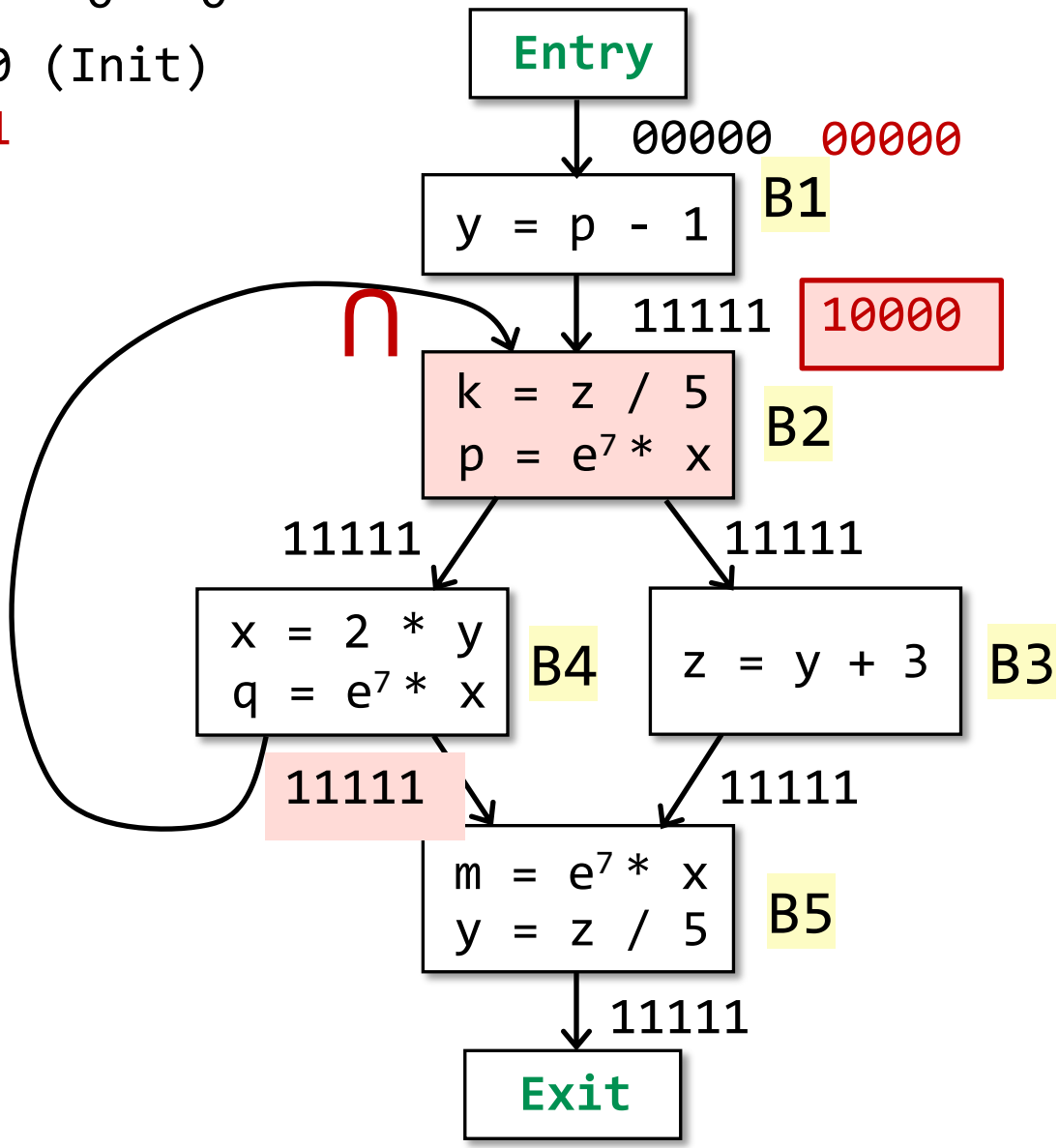

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Iteration 0 (Init)

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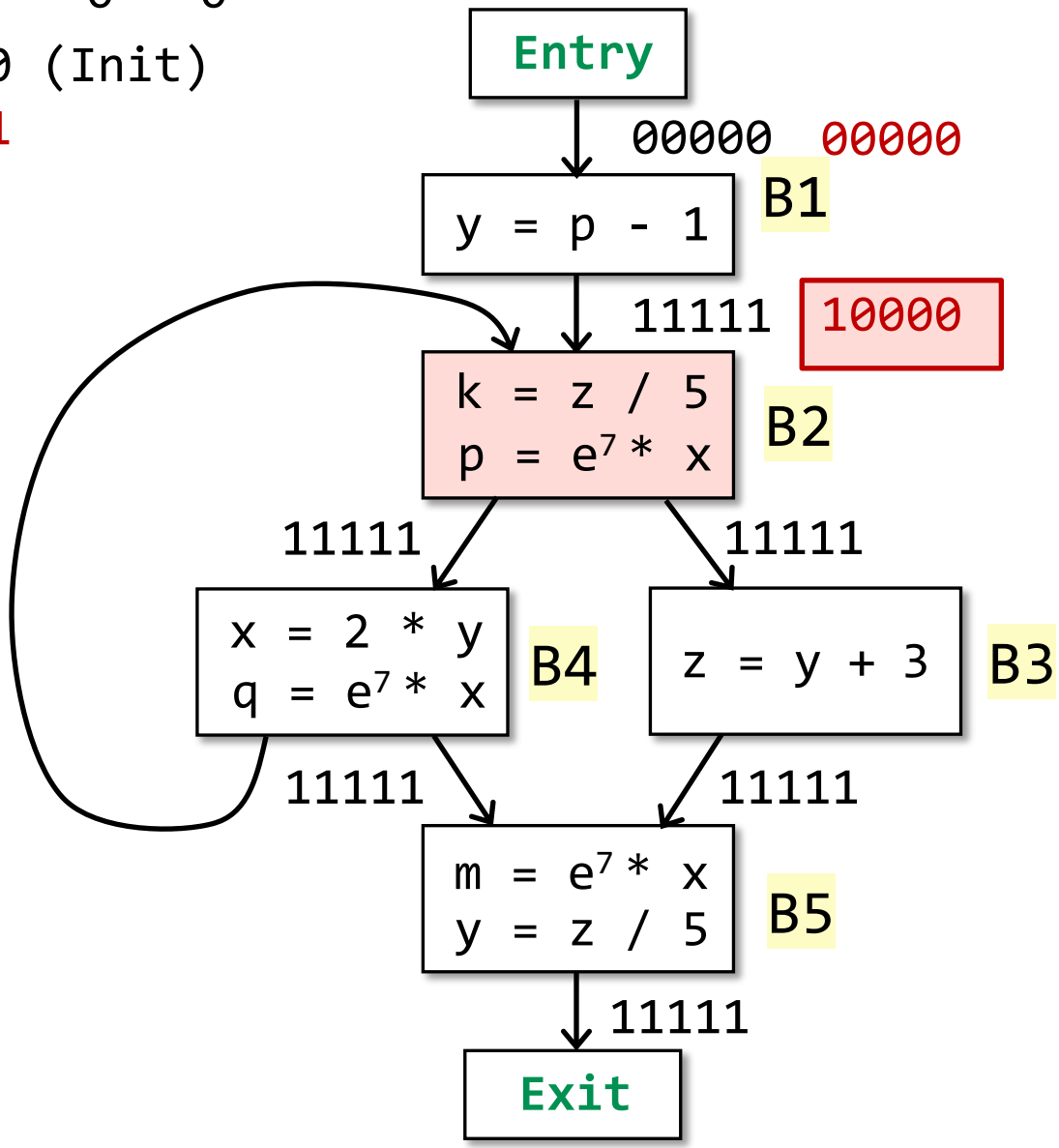

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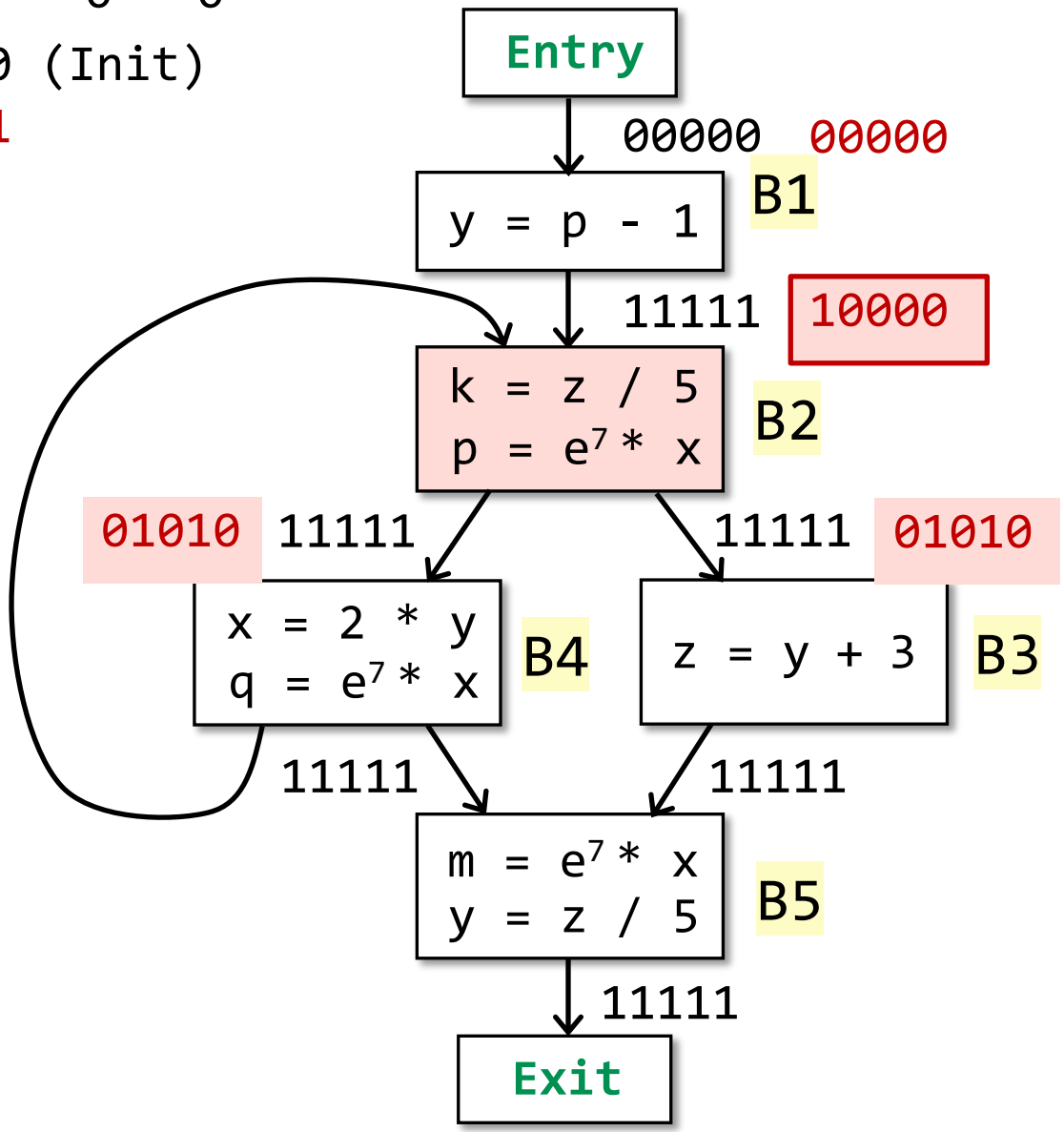

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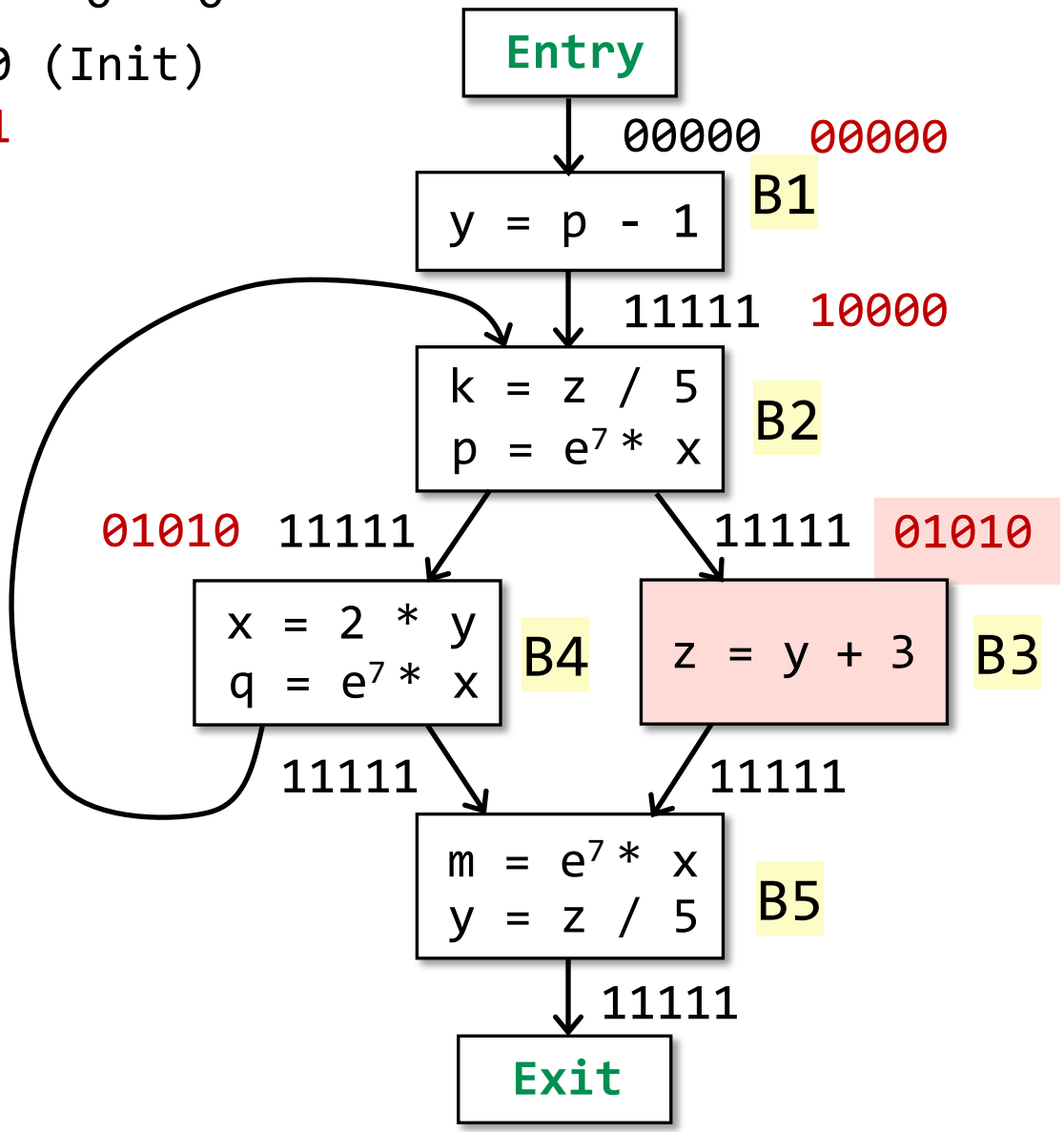

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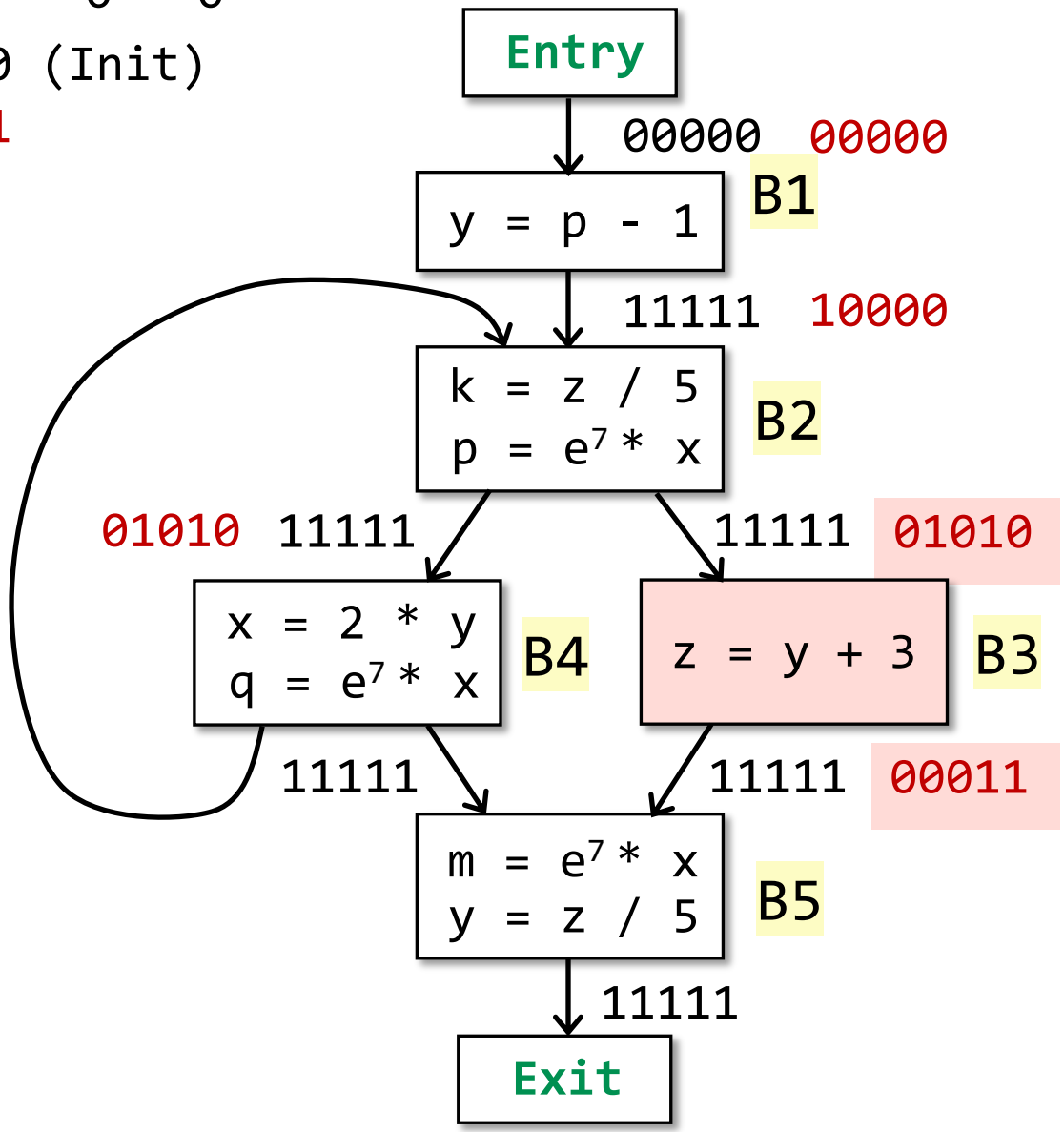

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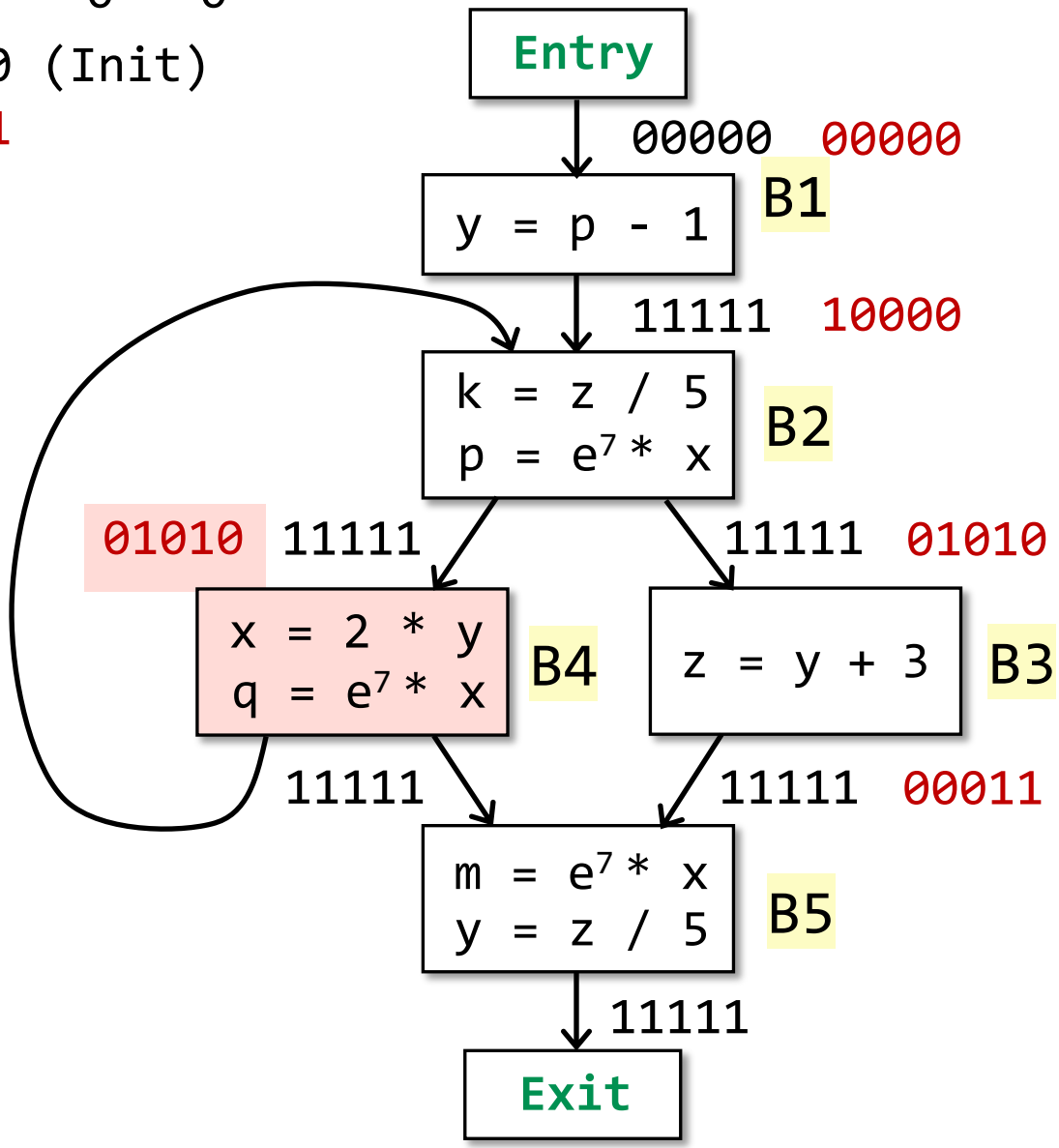

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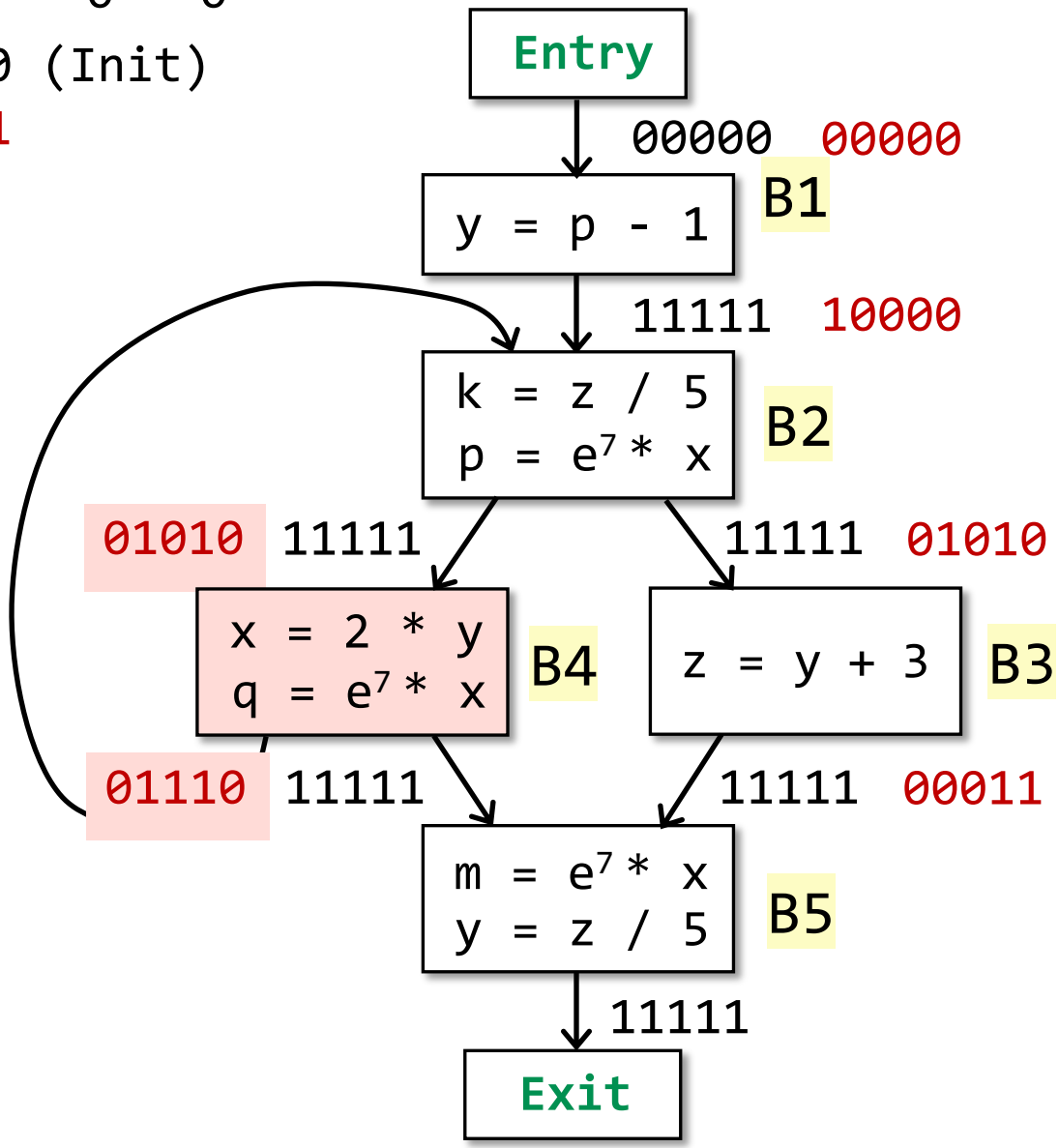

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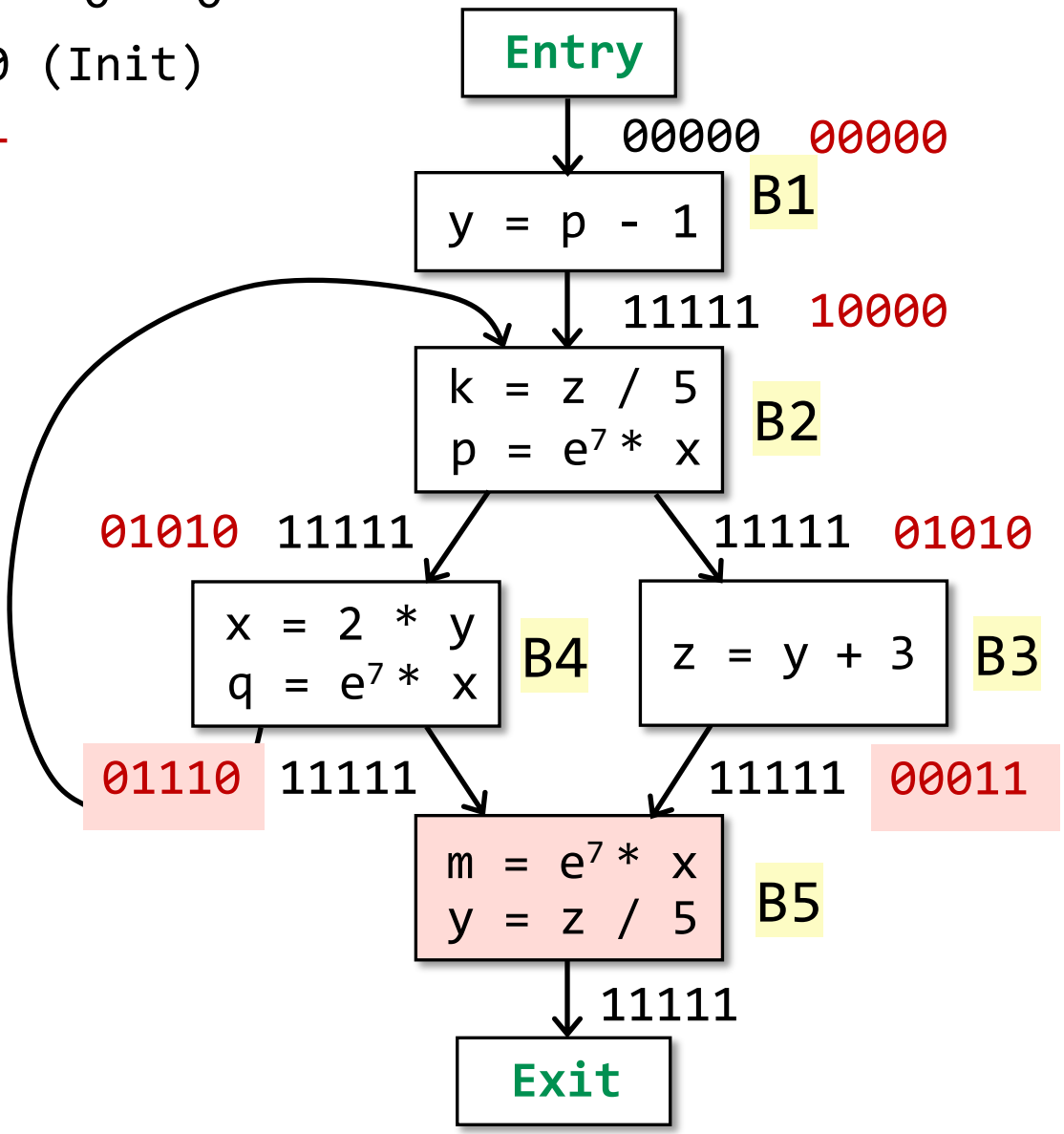

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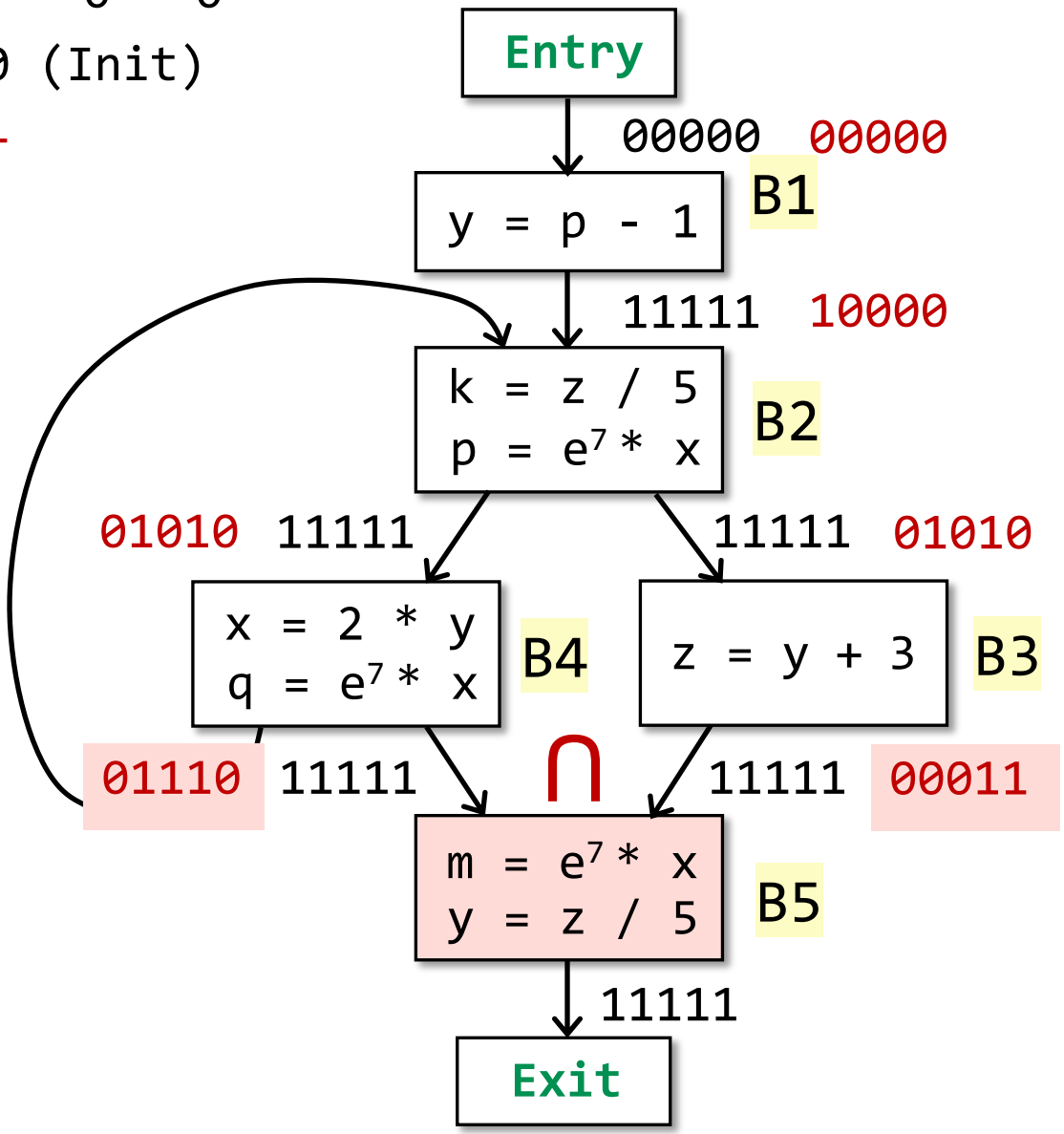

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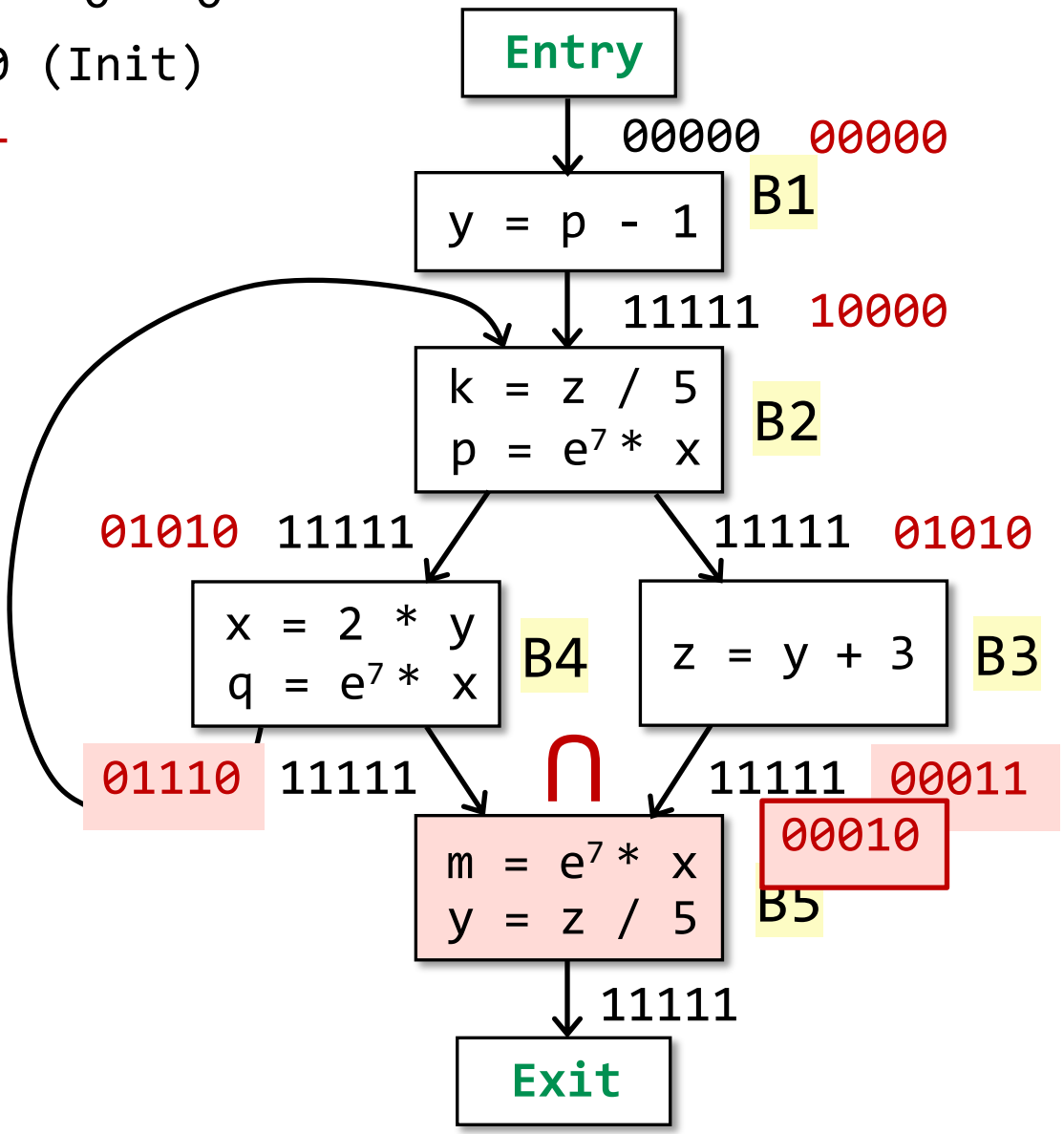

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0 0 0 0 0

Iteration 0 (Init)

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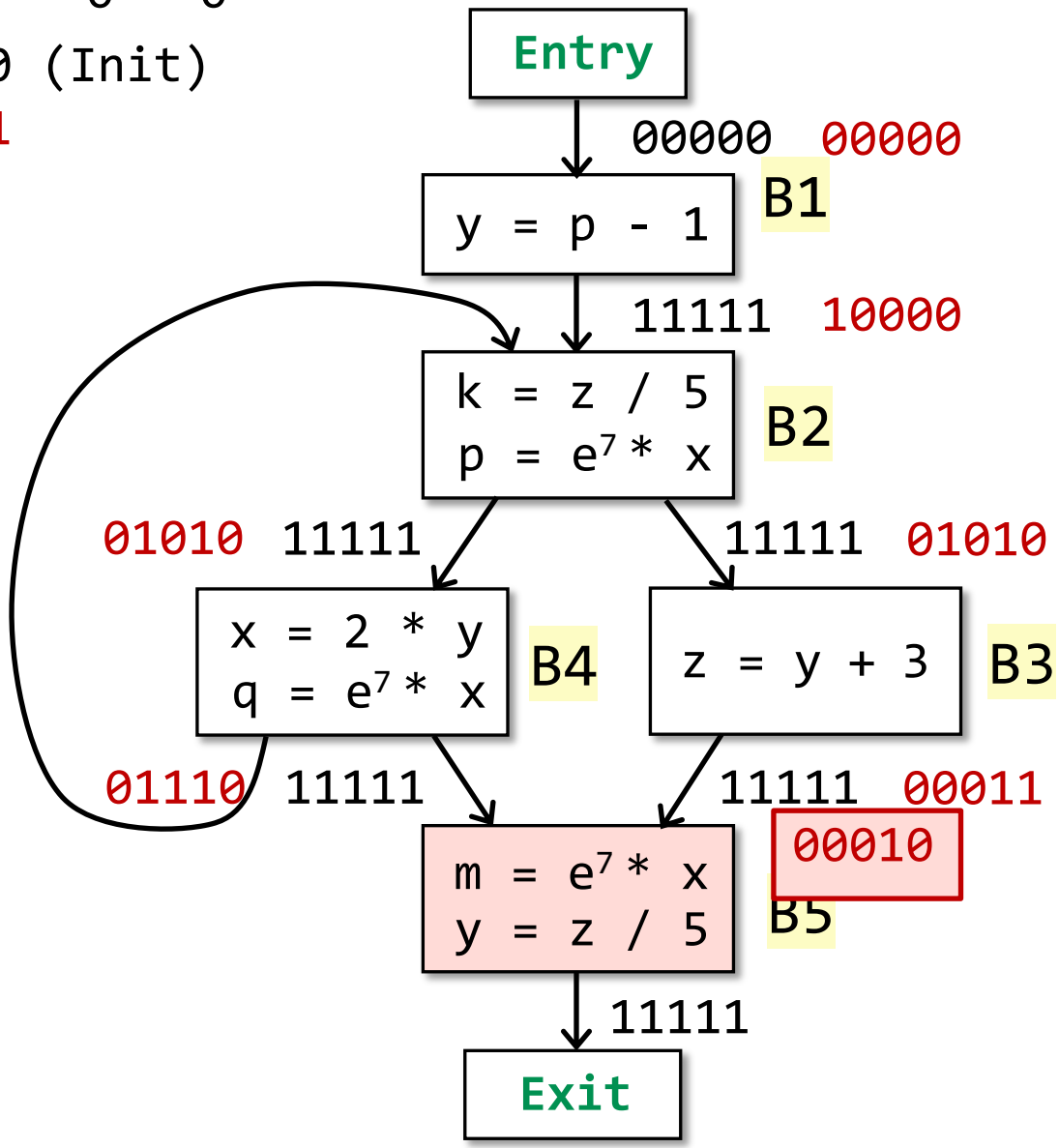

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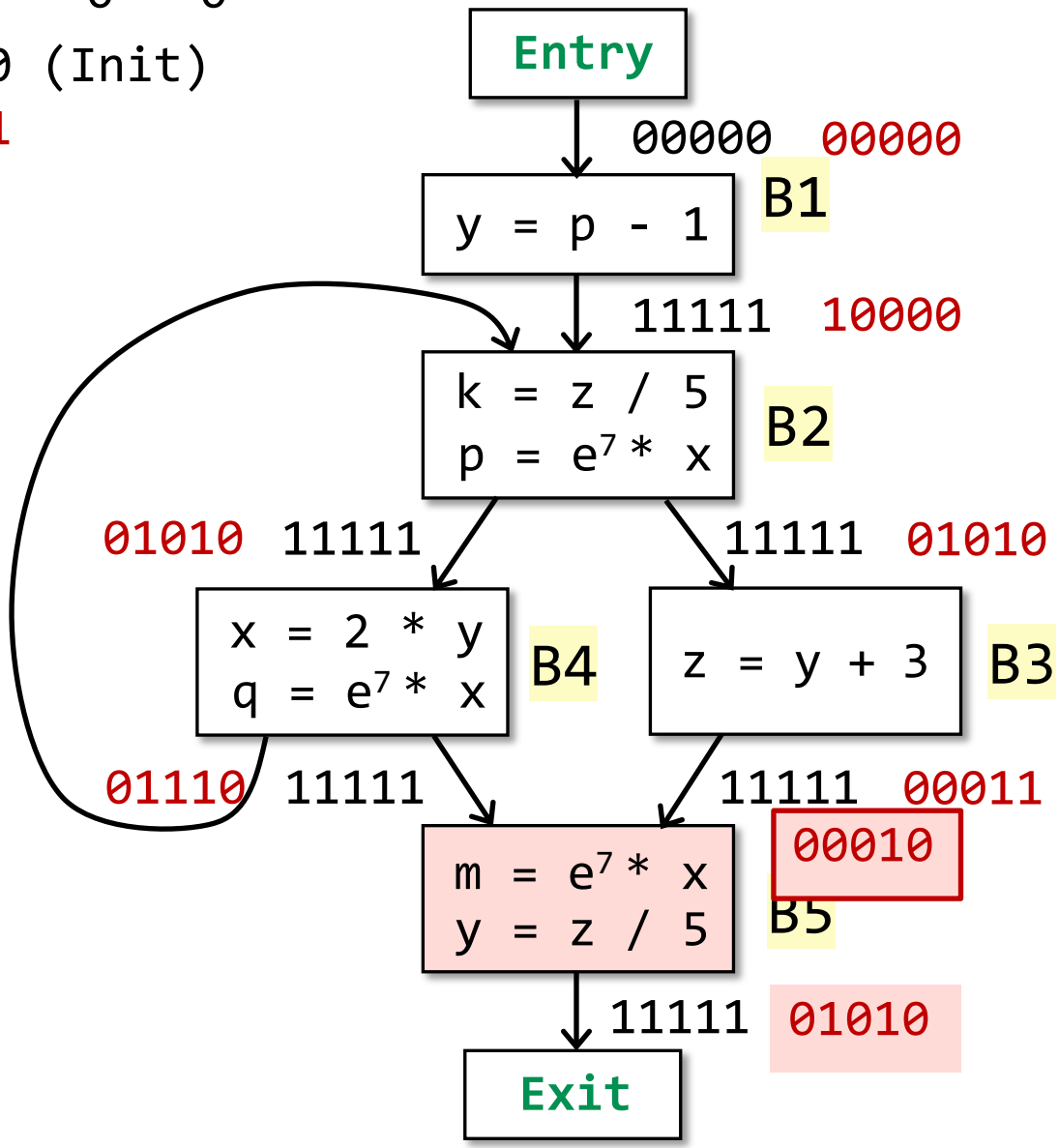
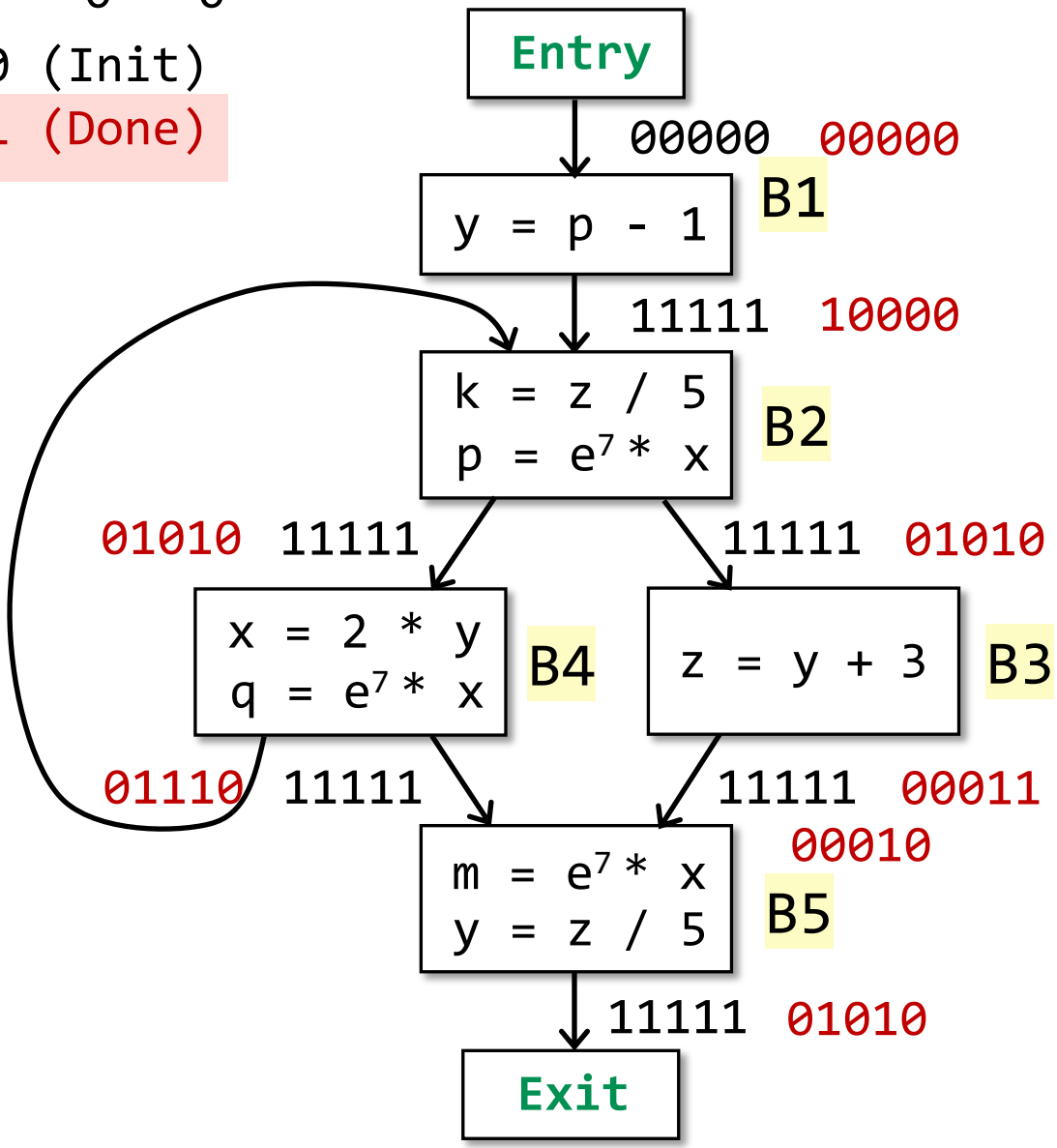
Iteration 1



p-1	z/5	2*y	e^7*x	y+3
0	0	0	0	0

Iteration 0 (Init)

Iteration 1 (Done)



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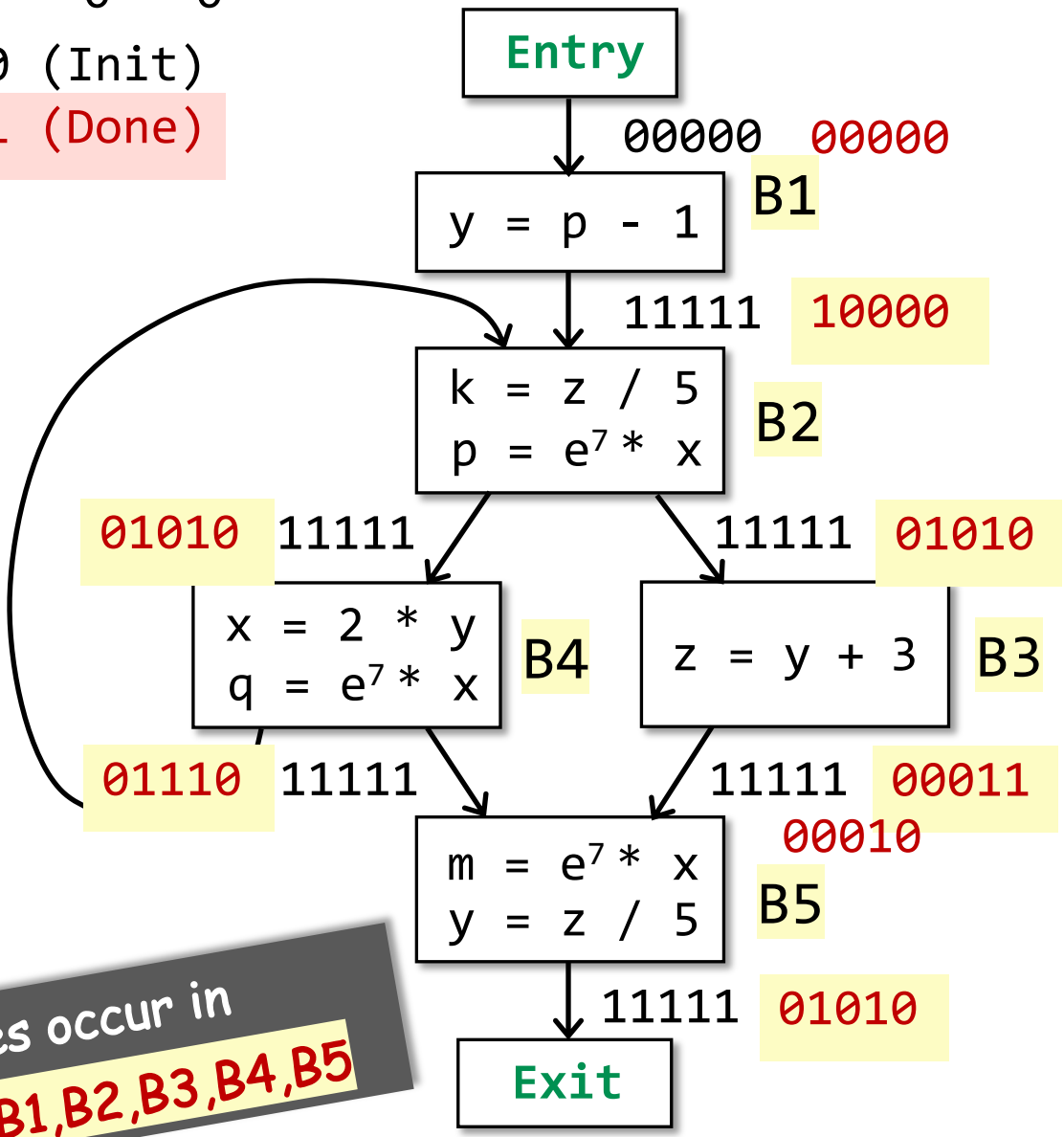
0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)



Changes occur in

OUT[] of B1,B2,B3,B4,B5

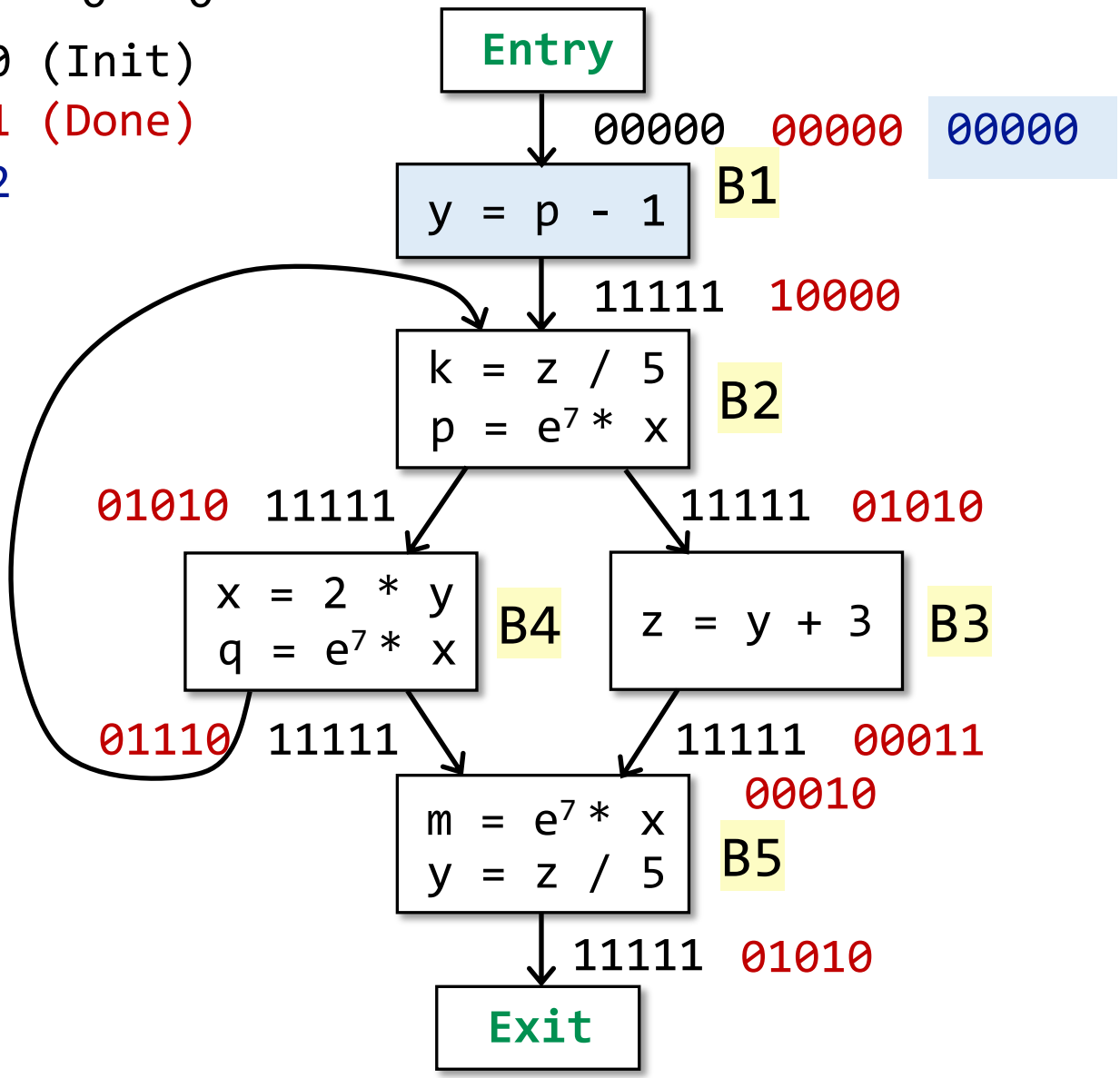
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



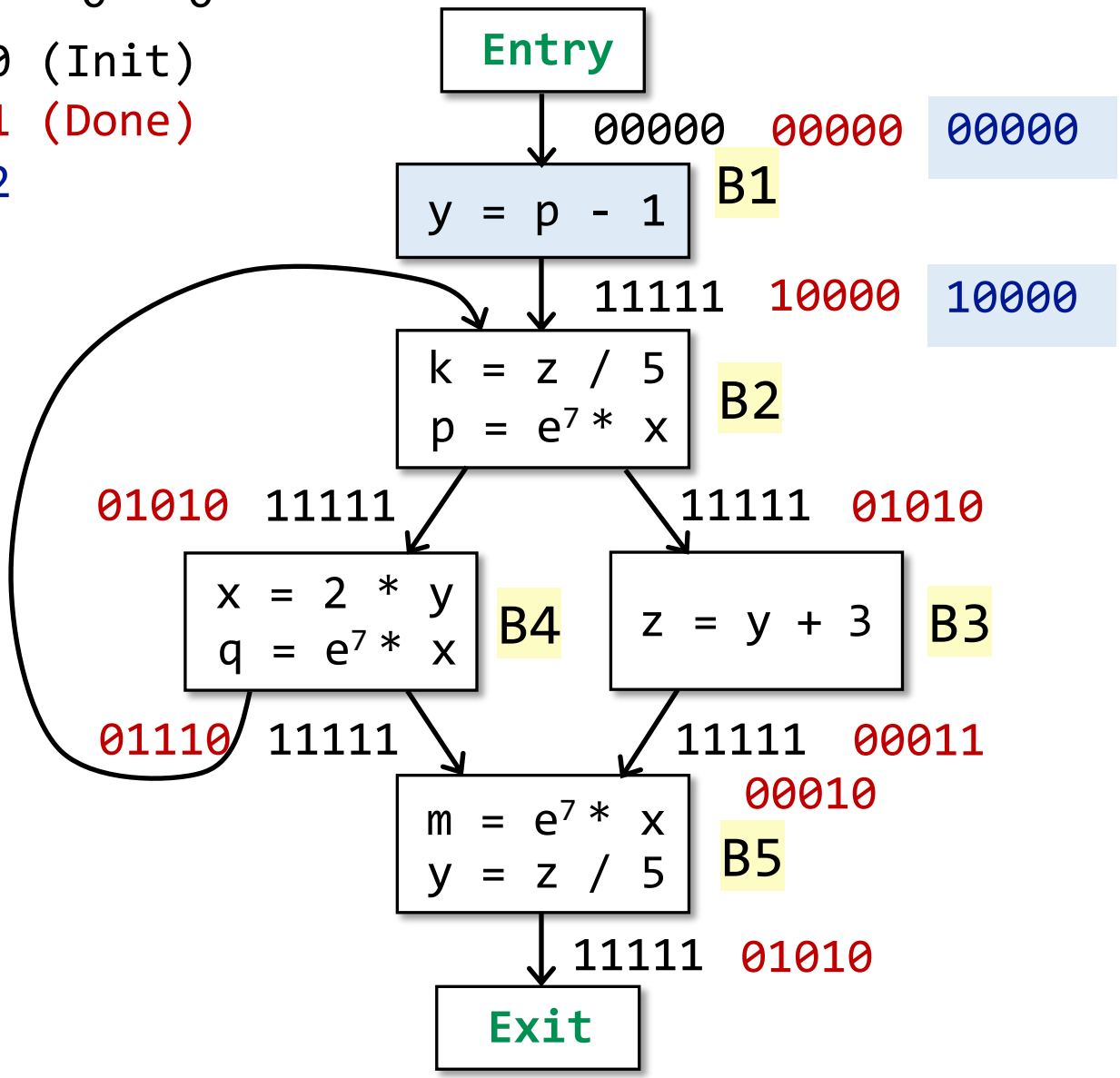
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



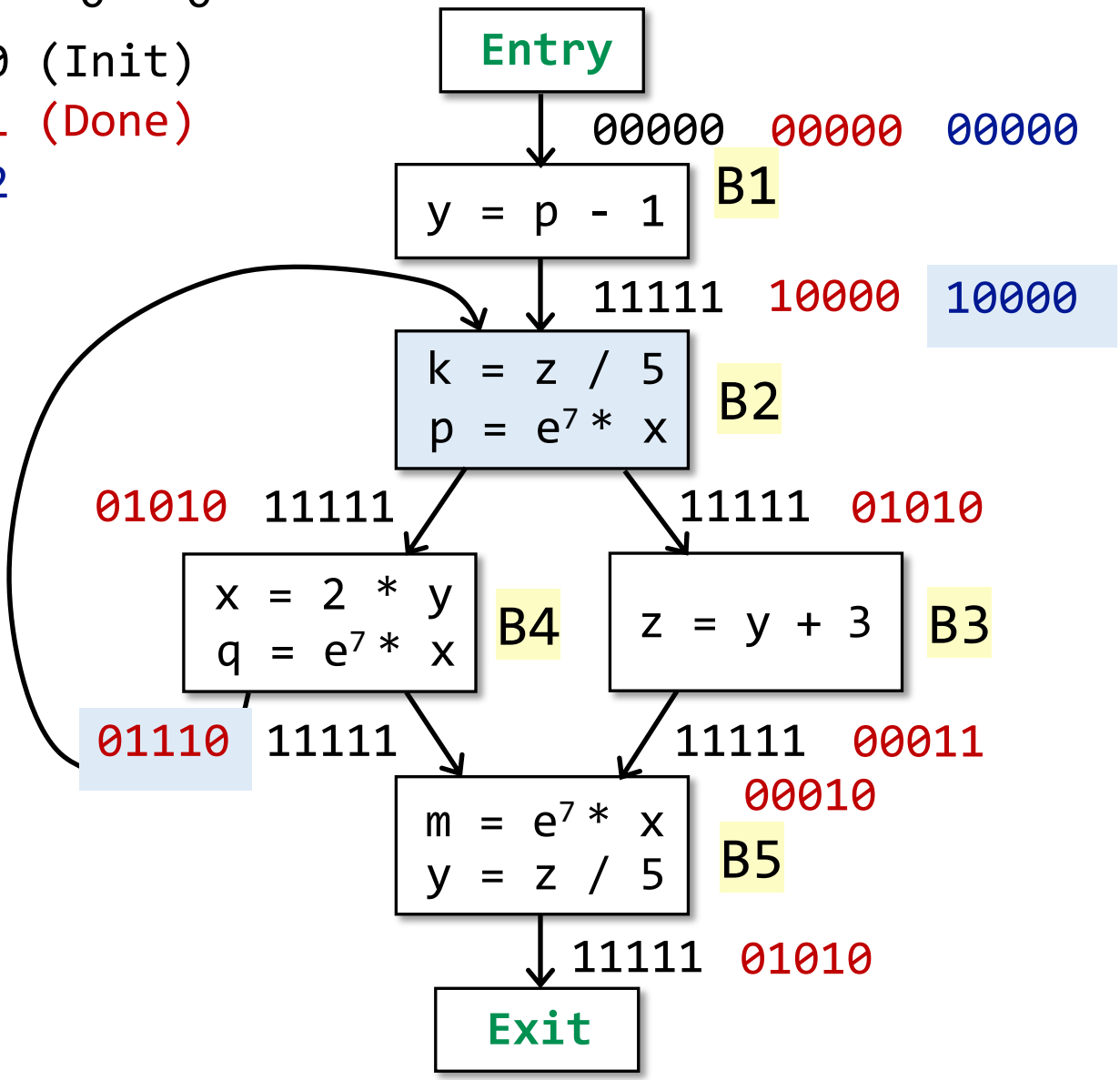
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



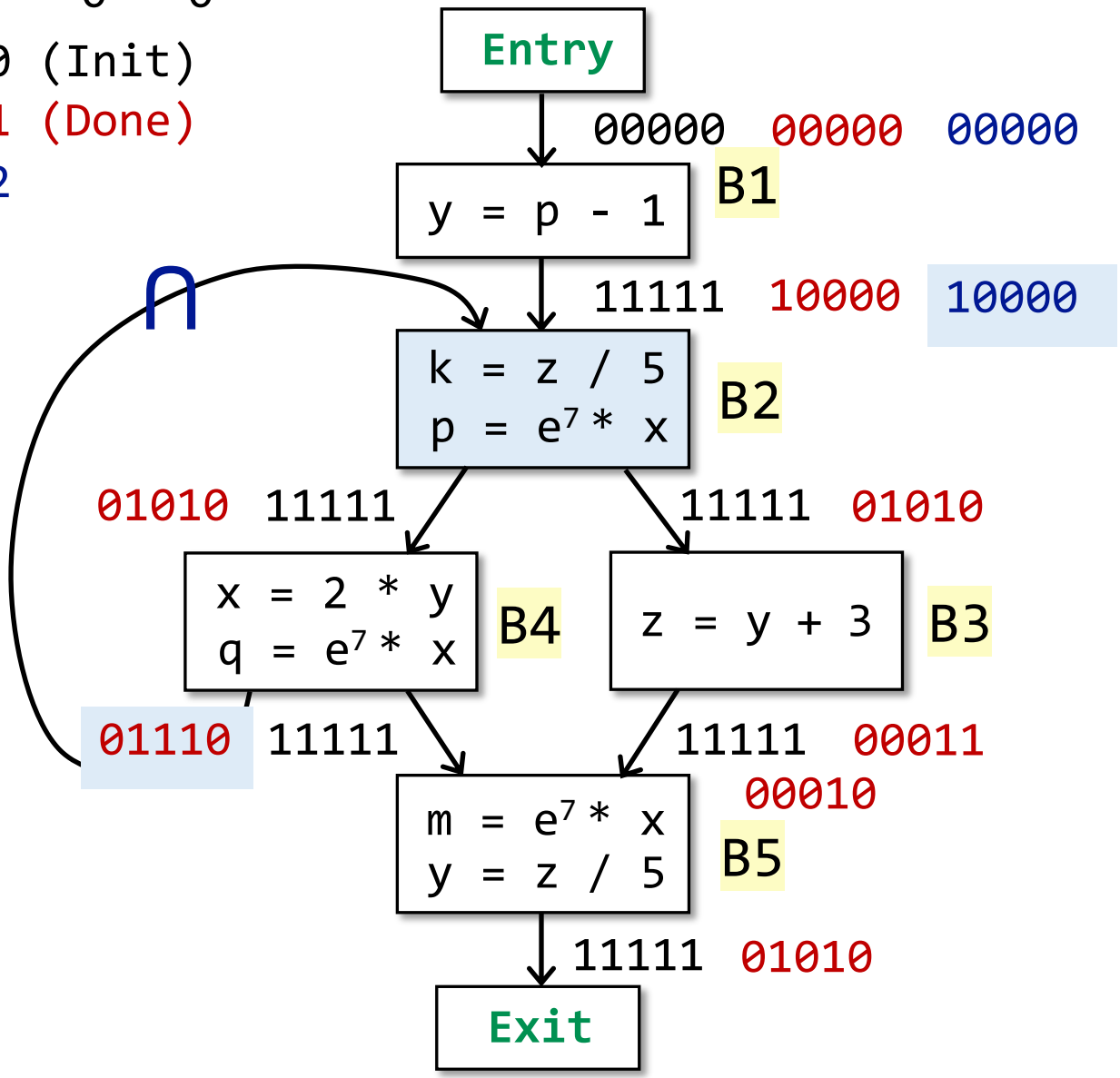
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

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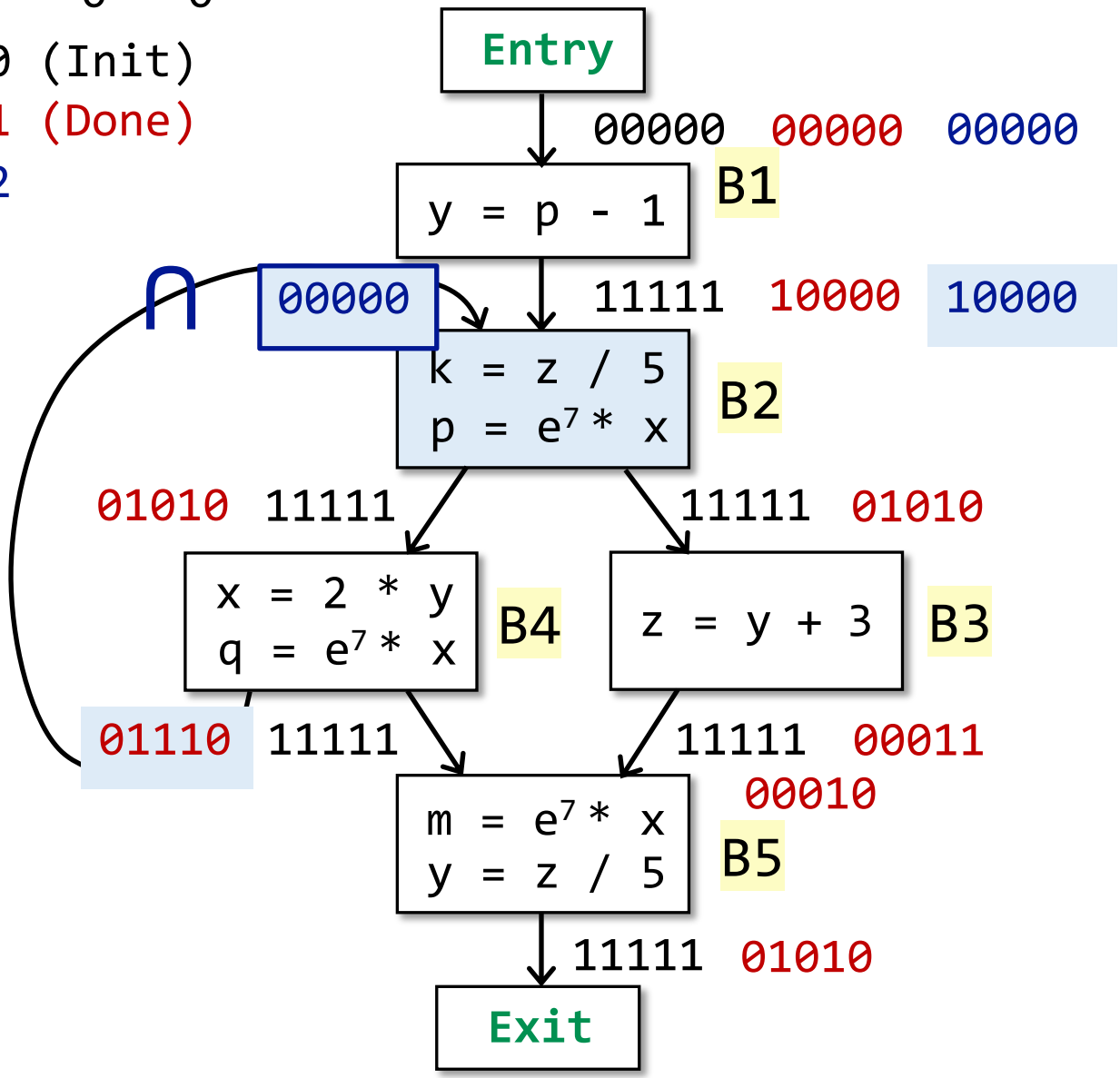
Iteration 2



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0 0 0 0 0

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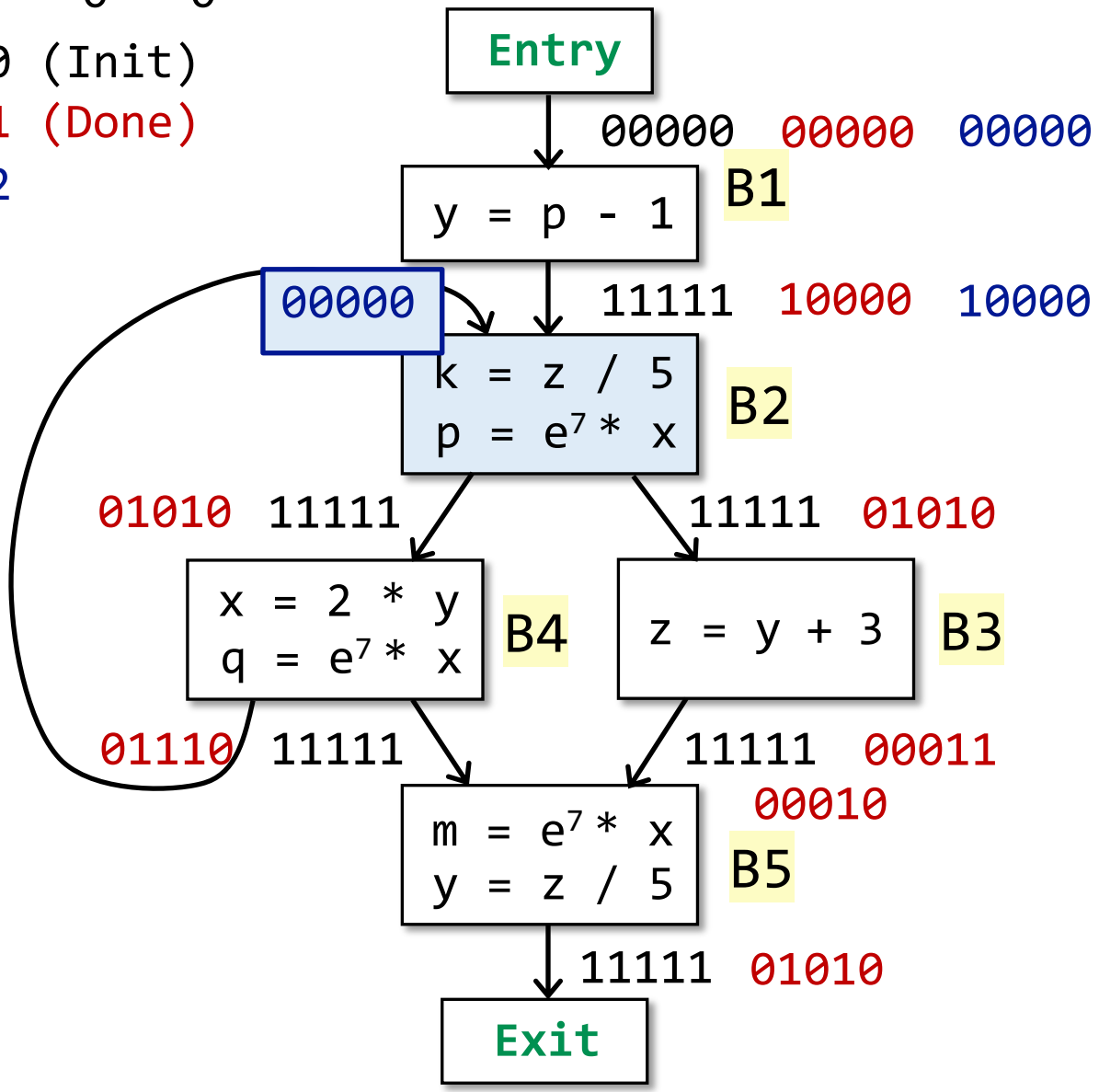

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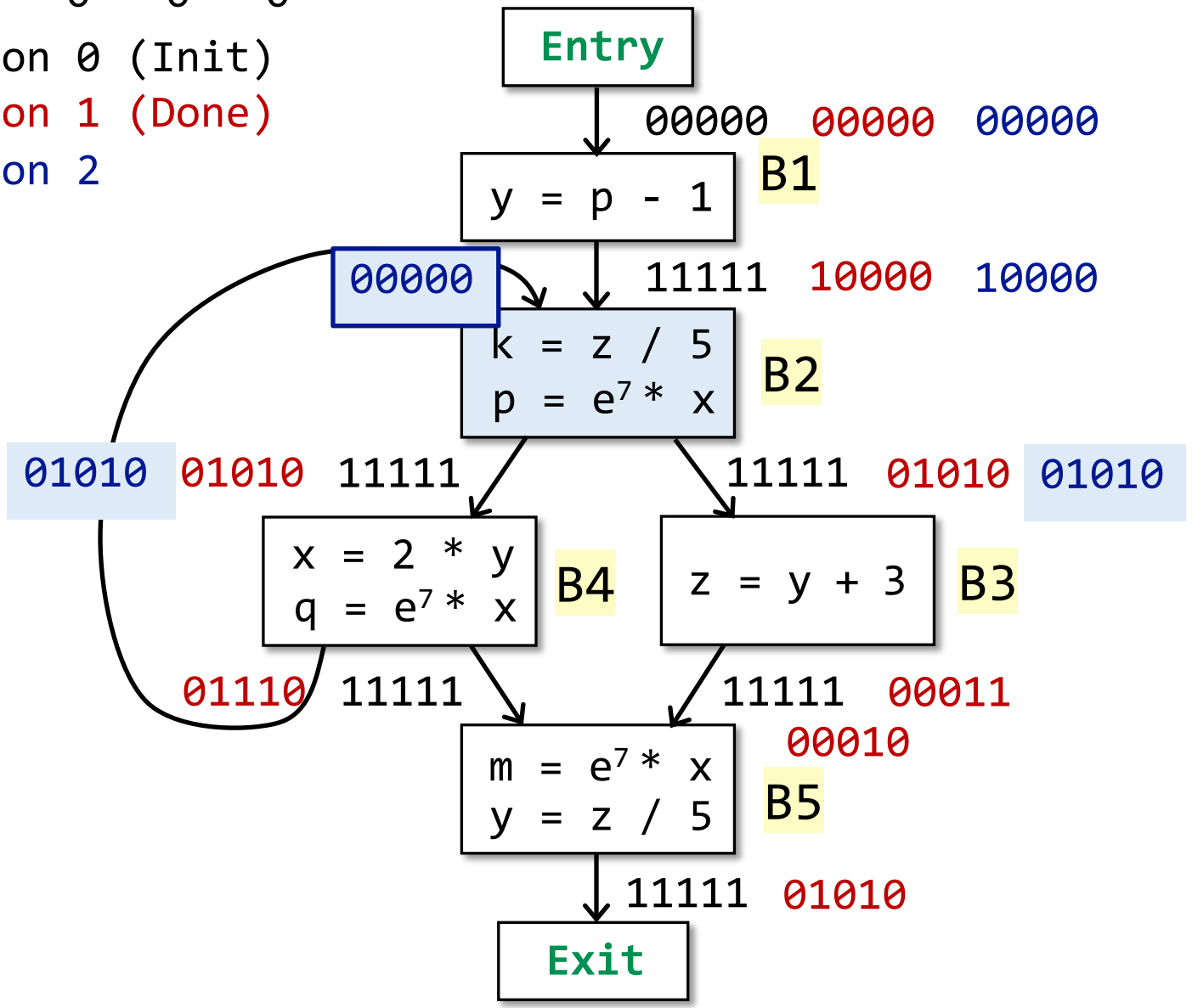
0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



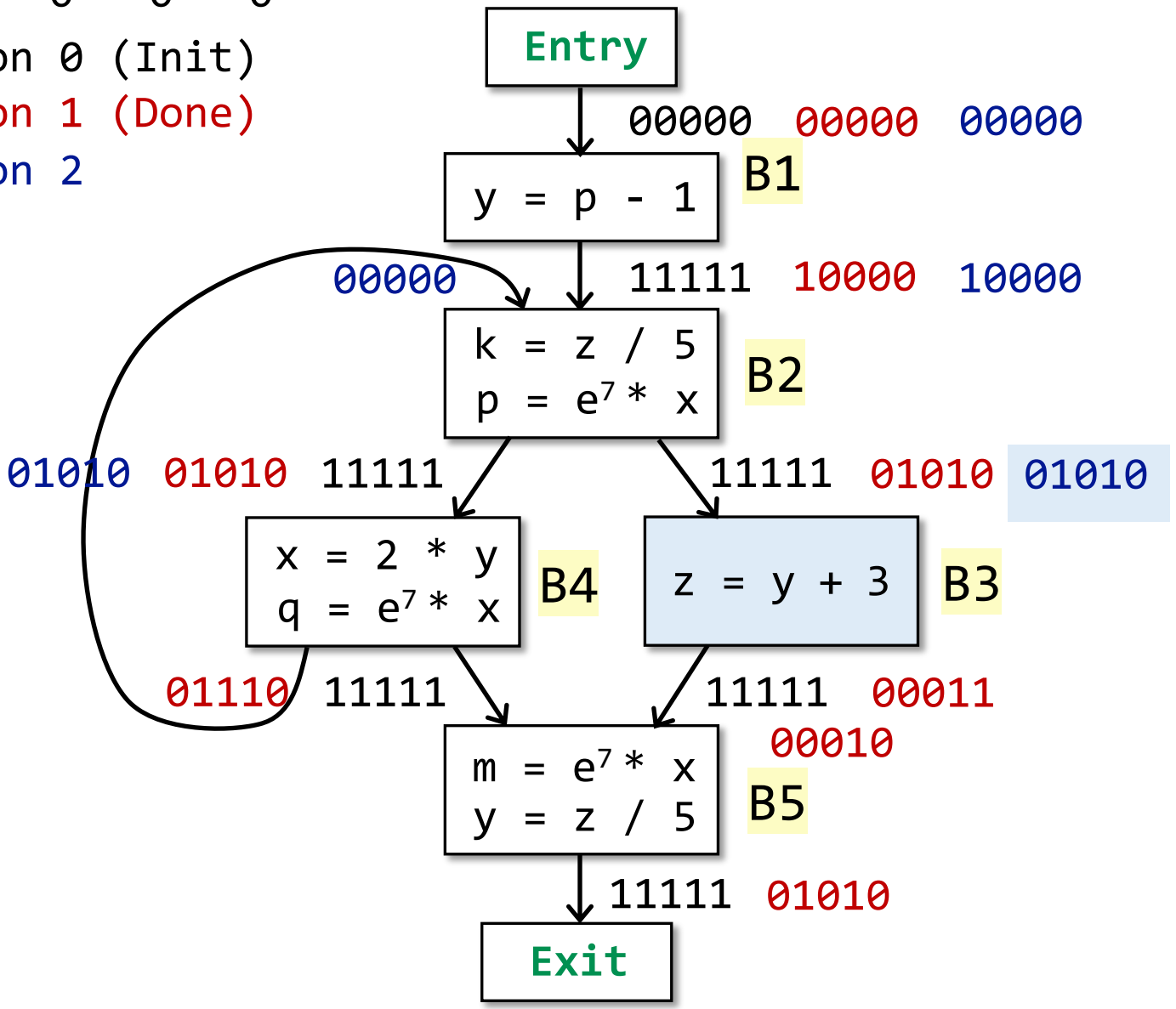
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



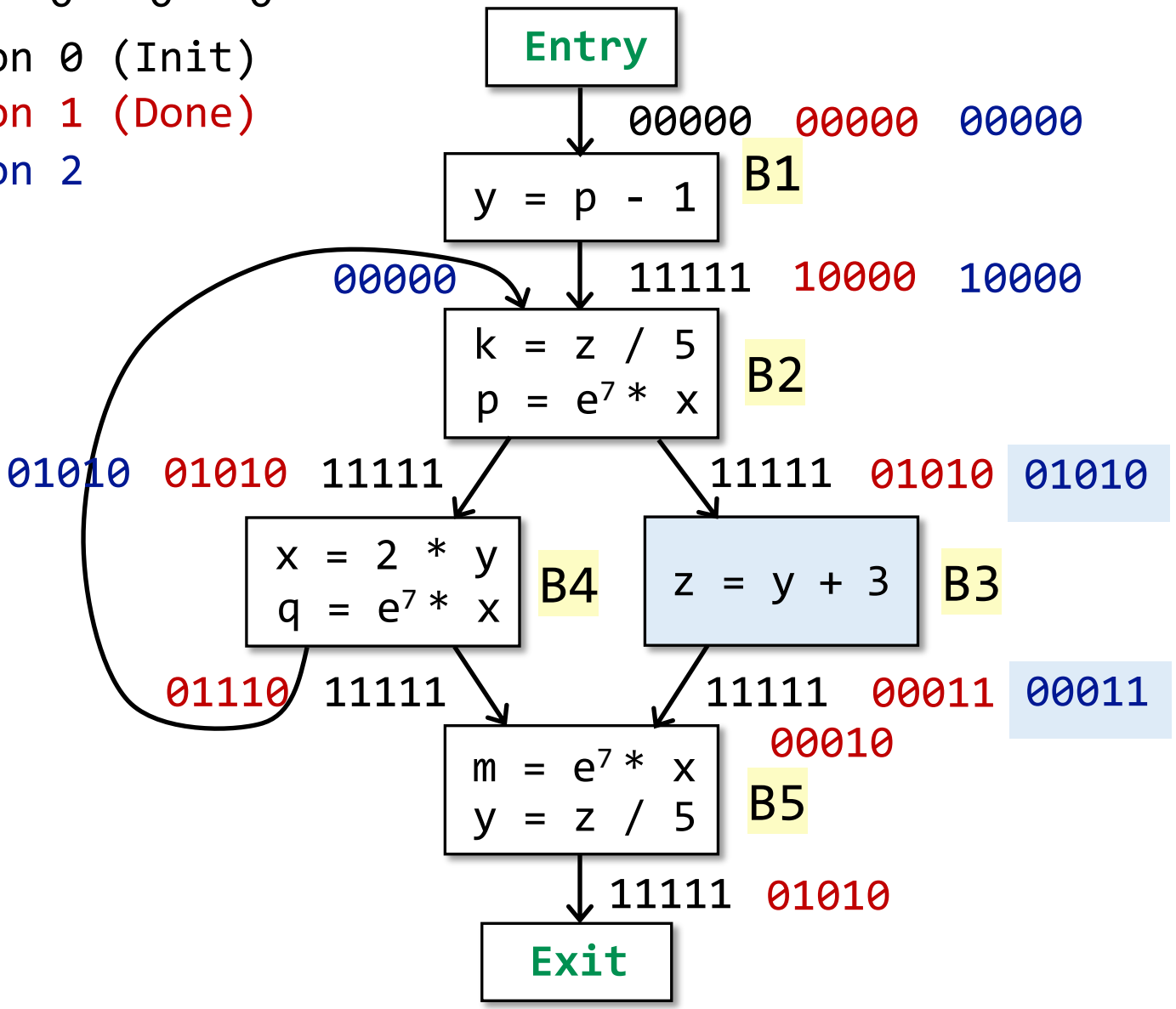
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



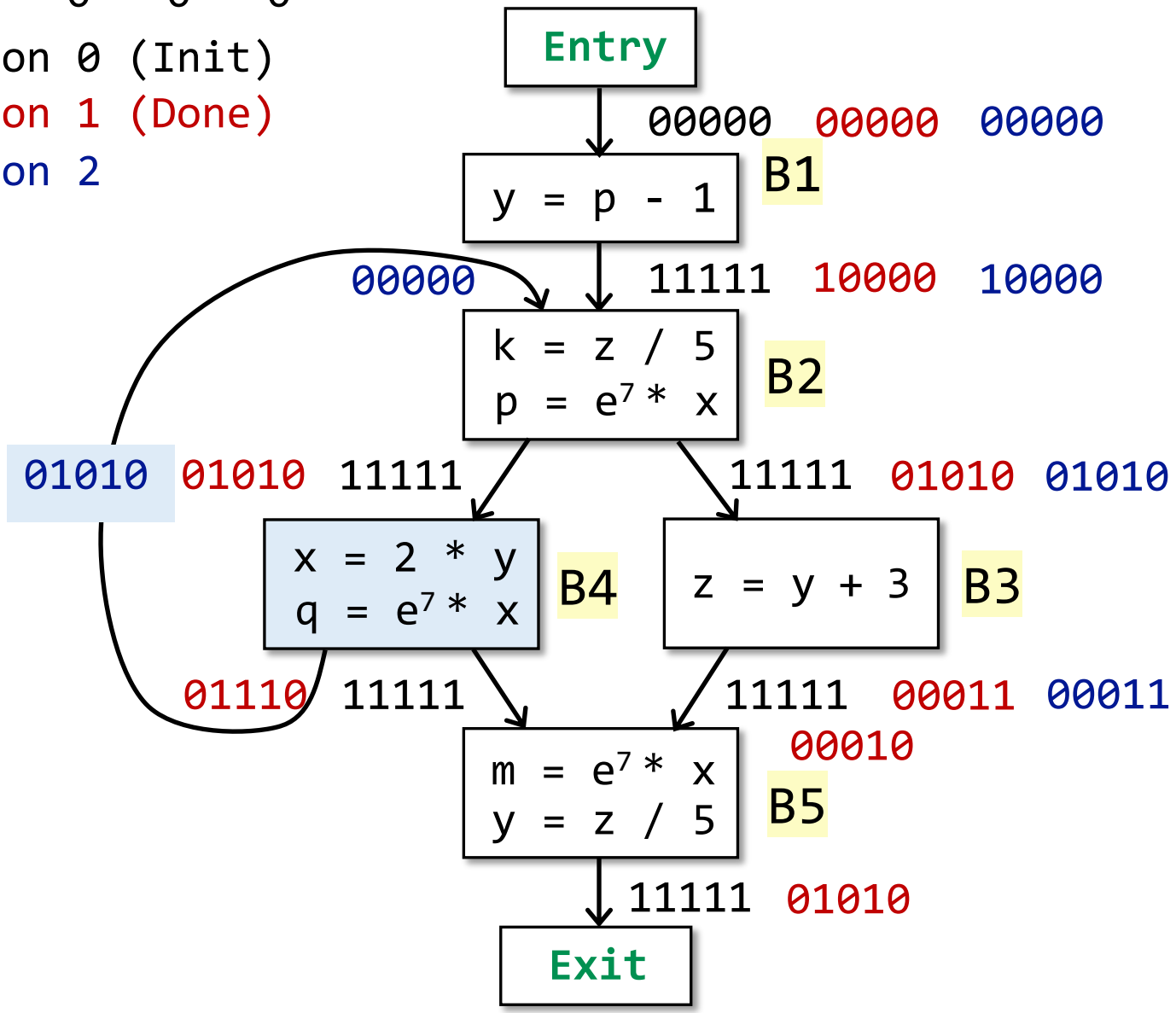
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



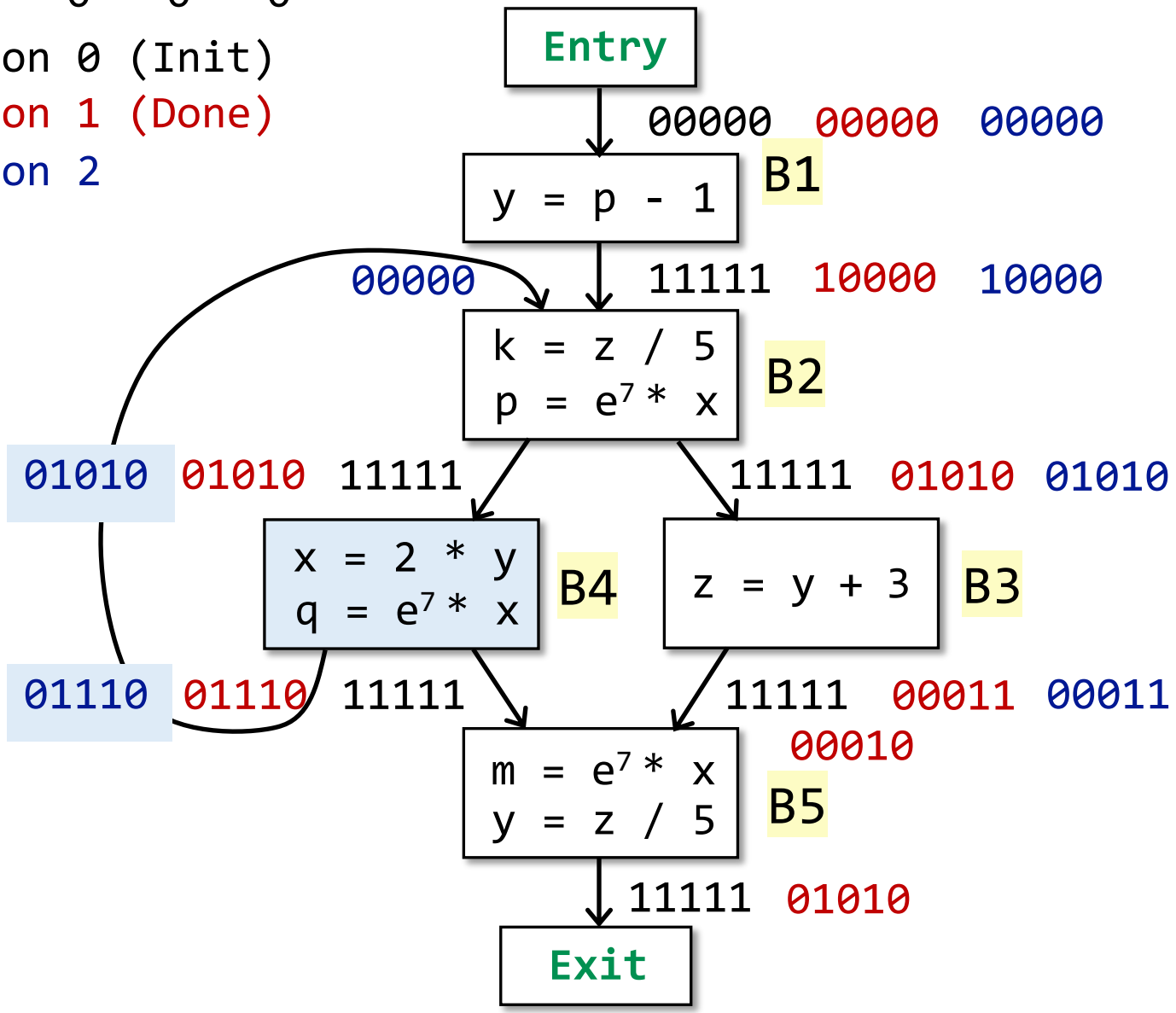
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



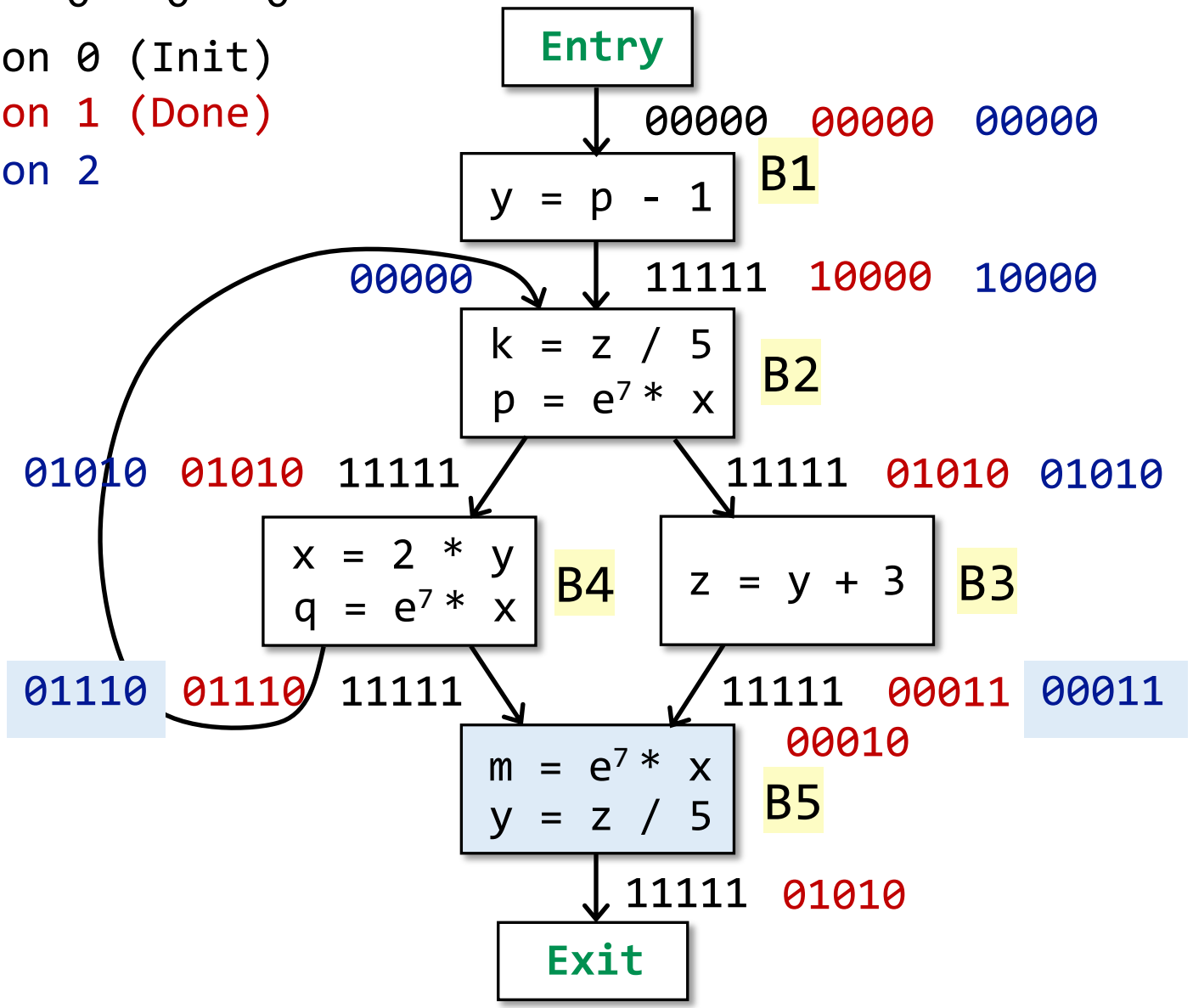
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



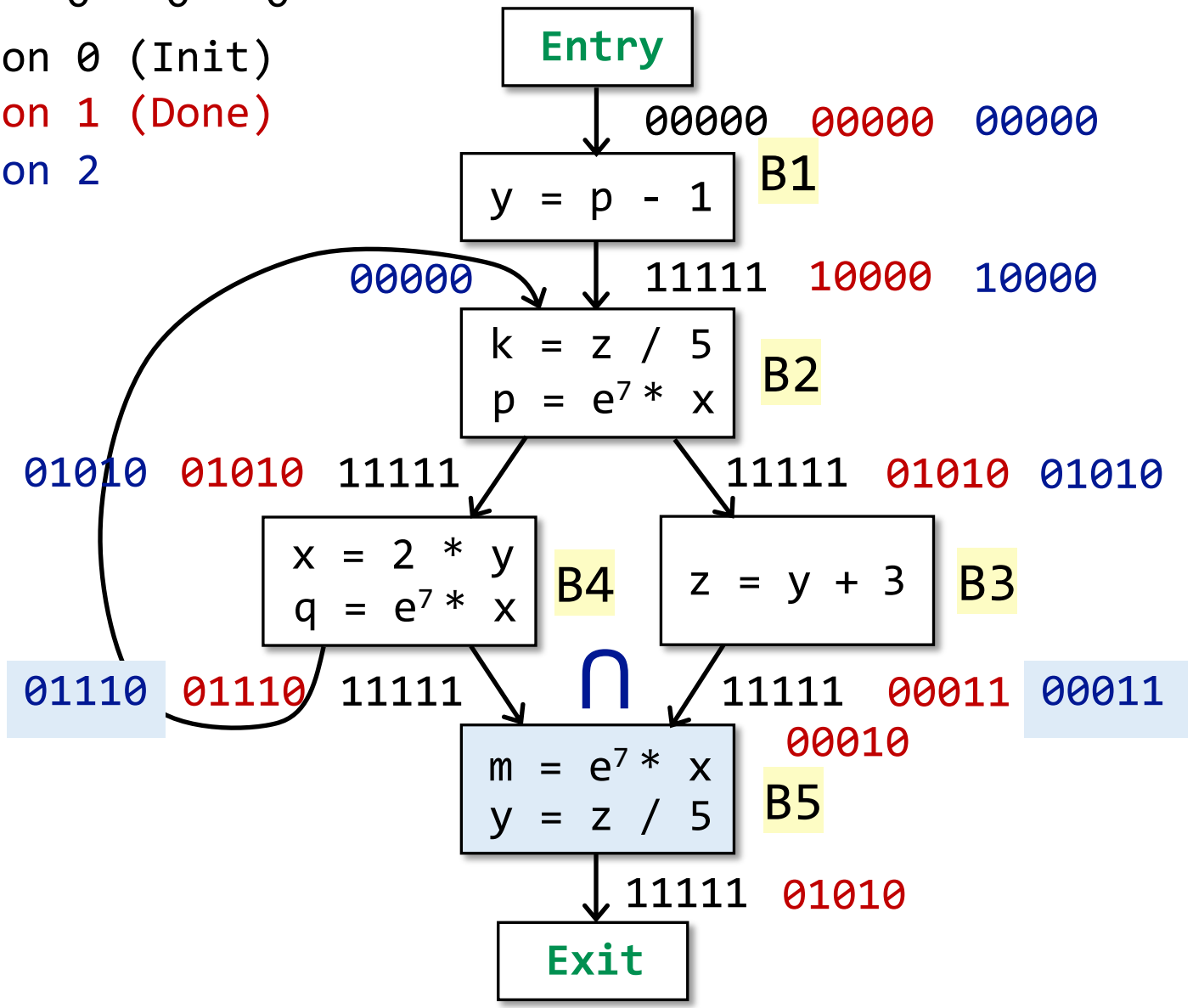
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



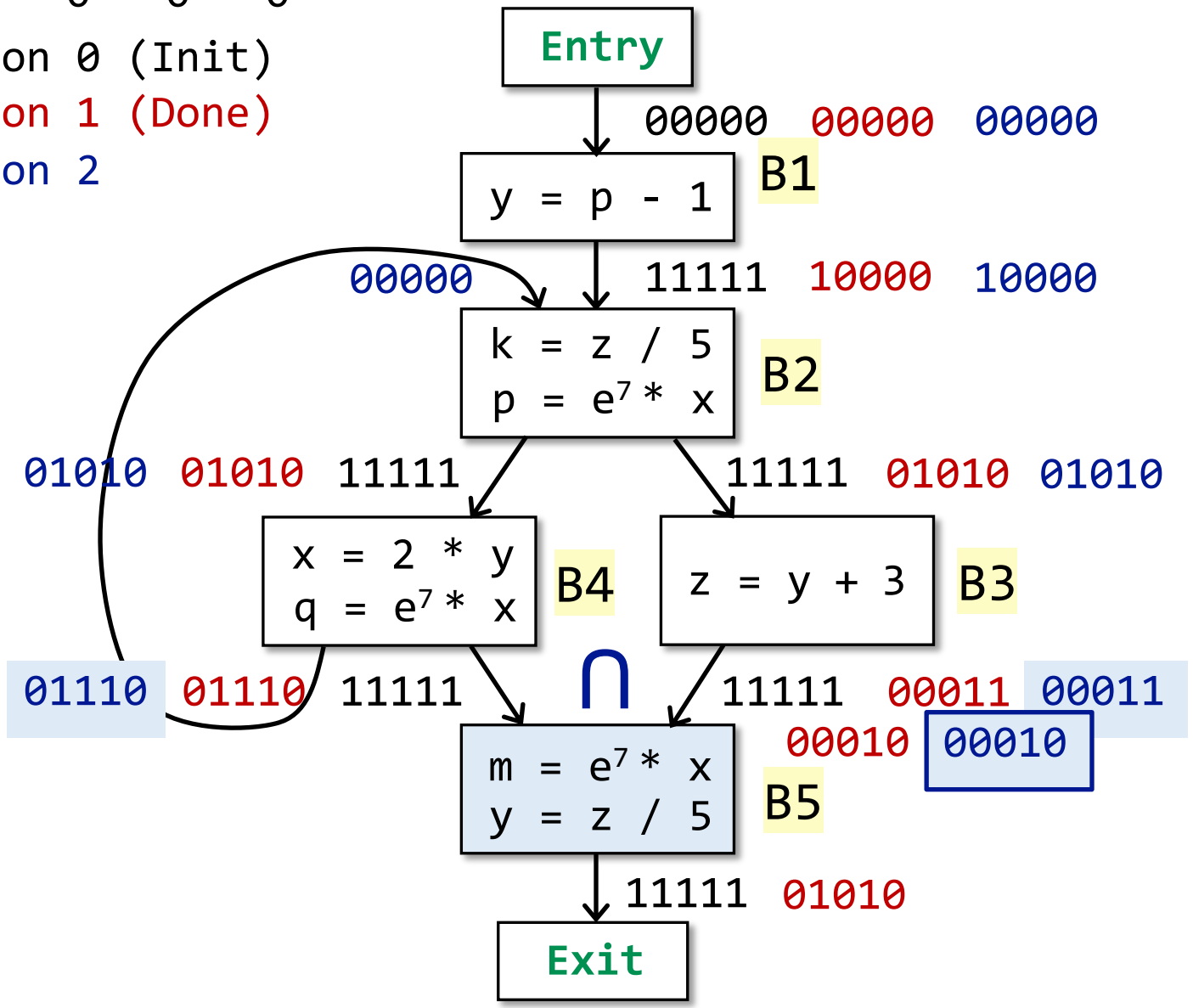
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



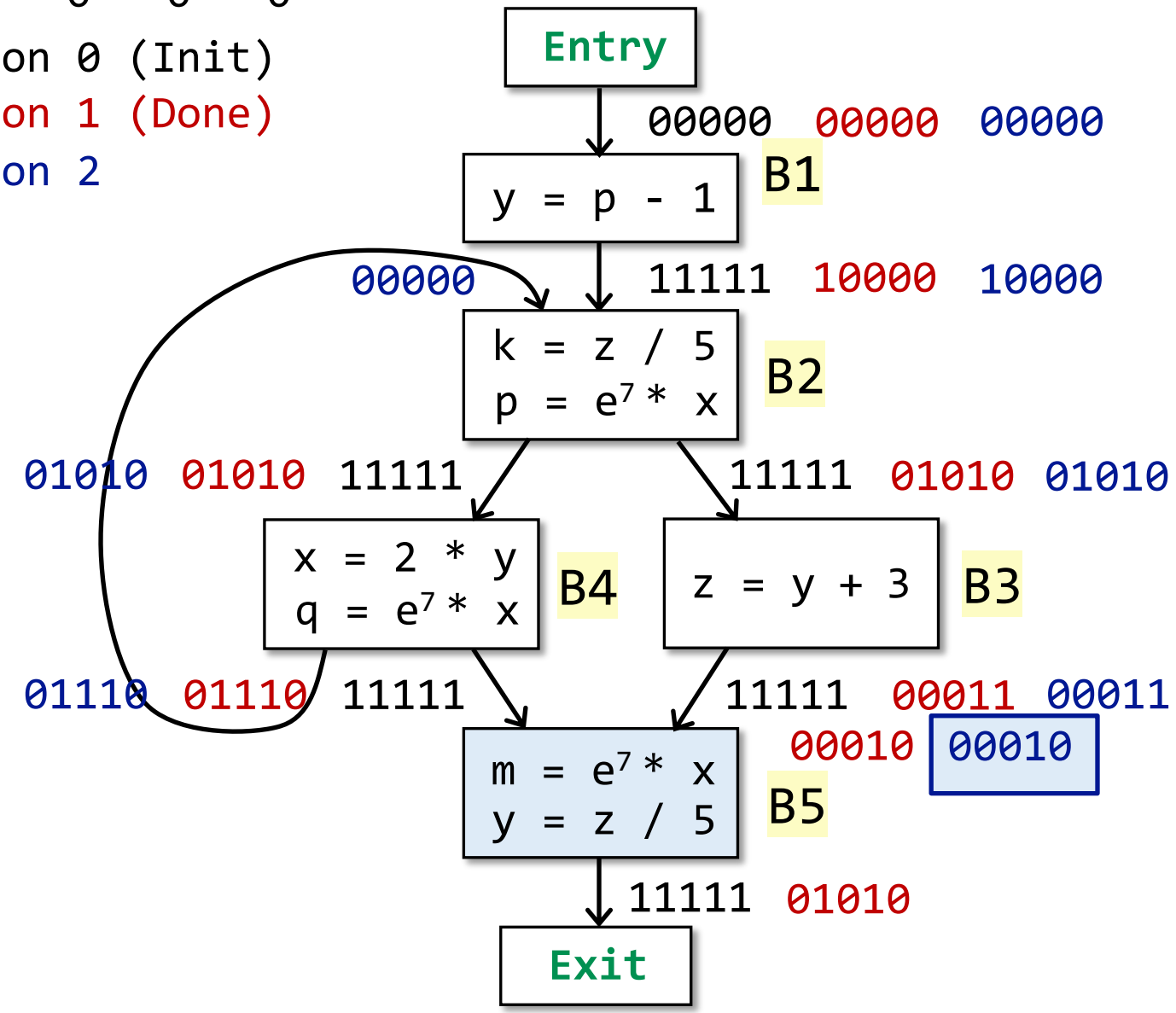
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



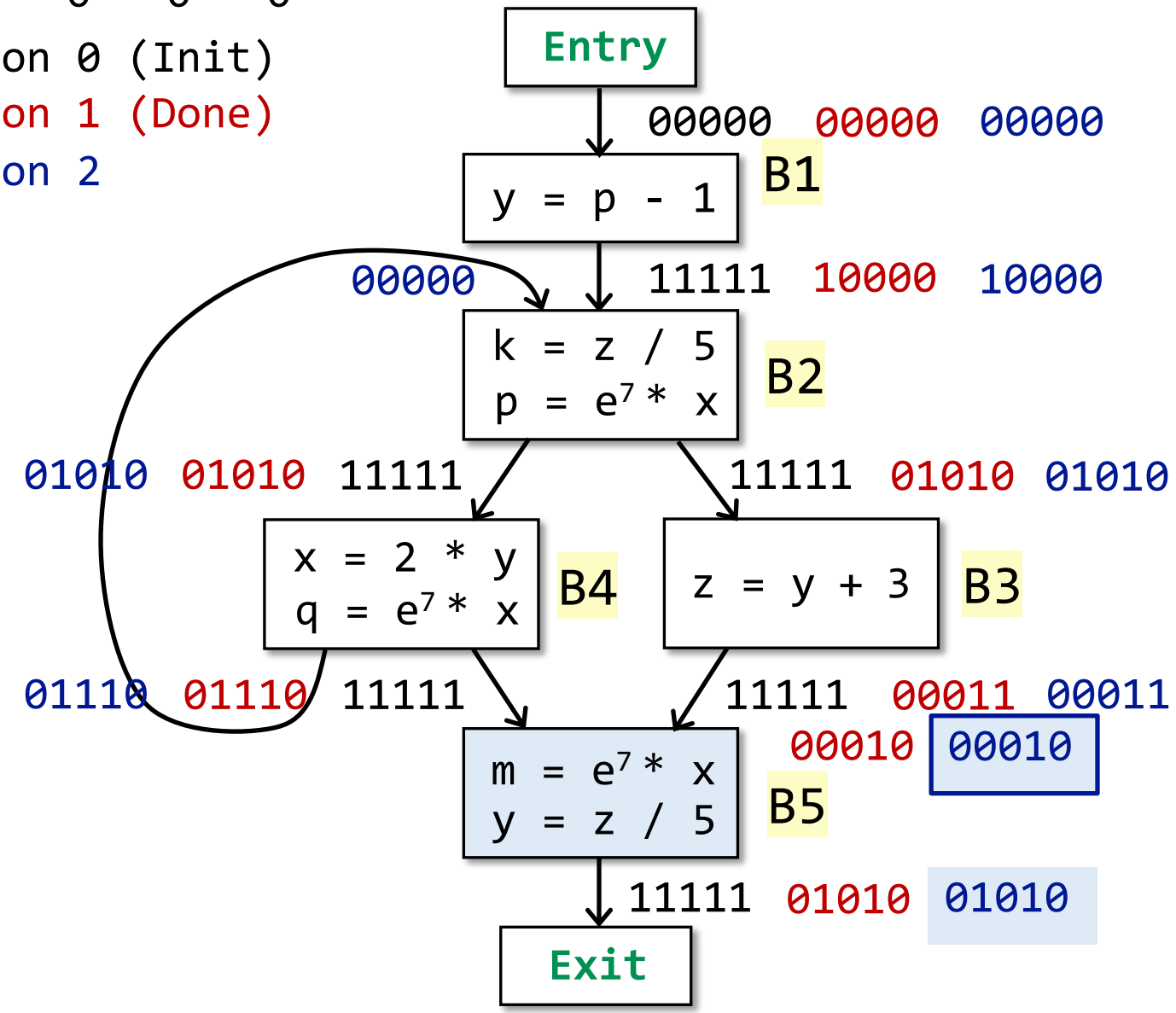
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2



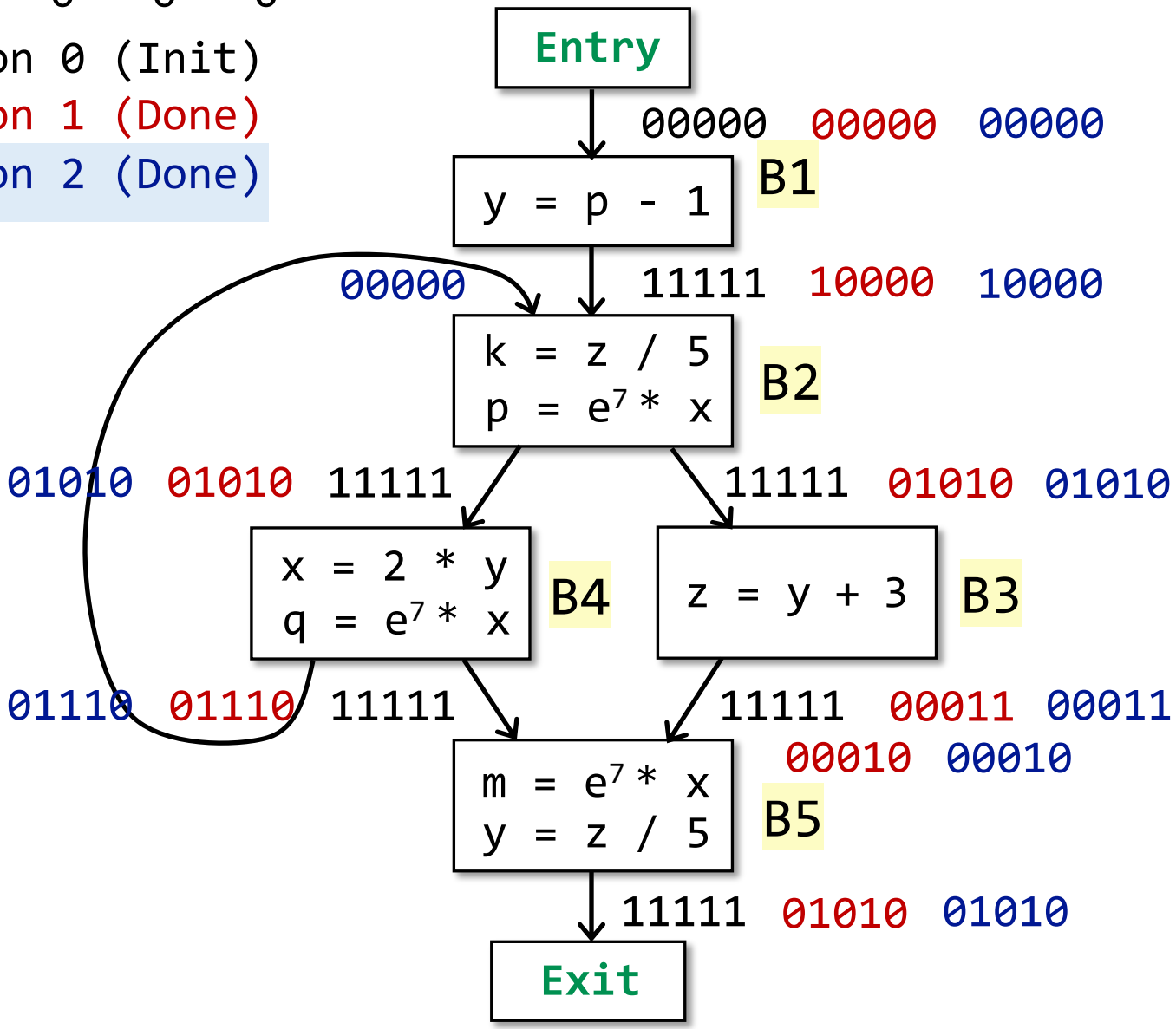
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2 (Done)



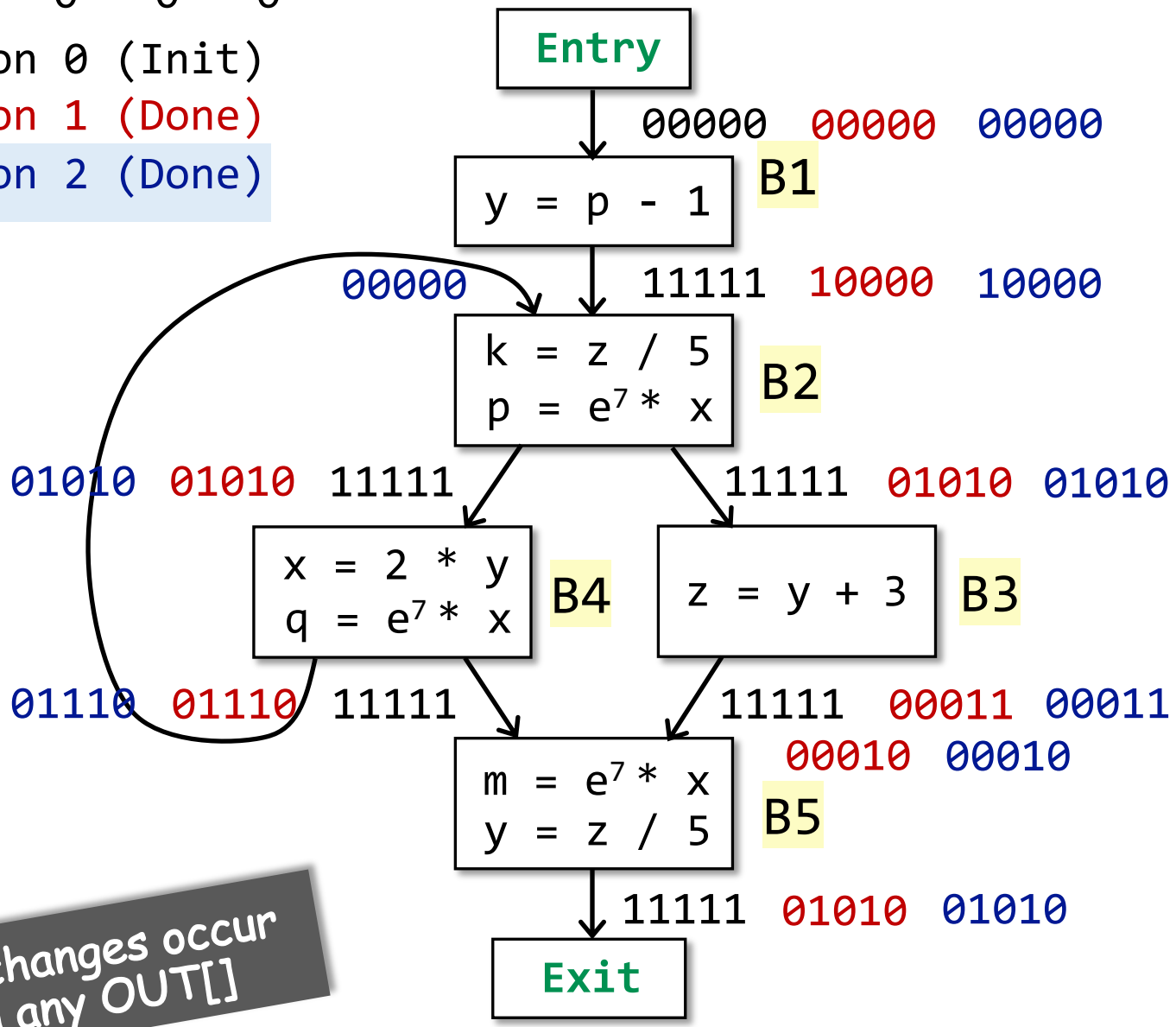
p-1 z/5 2*y e^7*x y+3

0 0 0 0 0

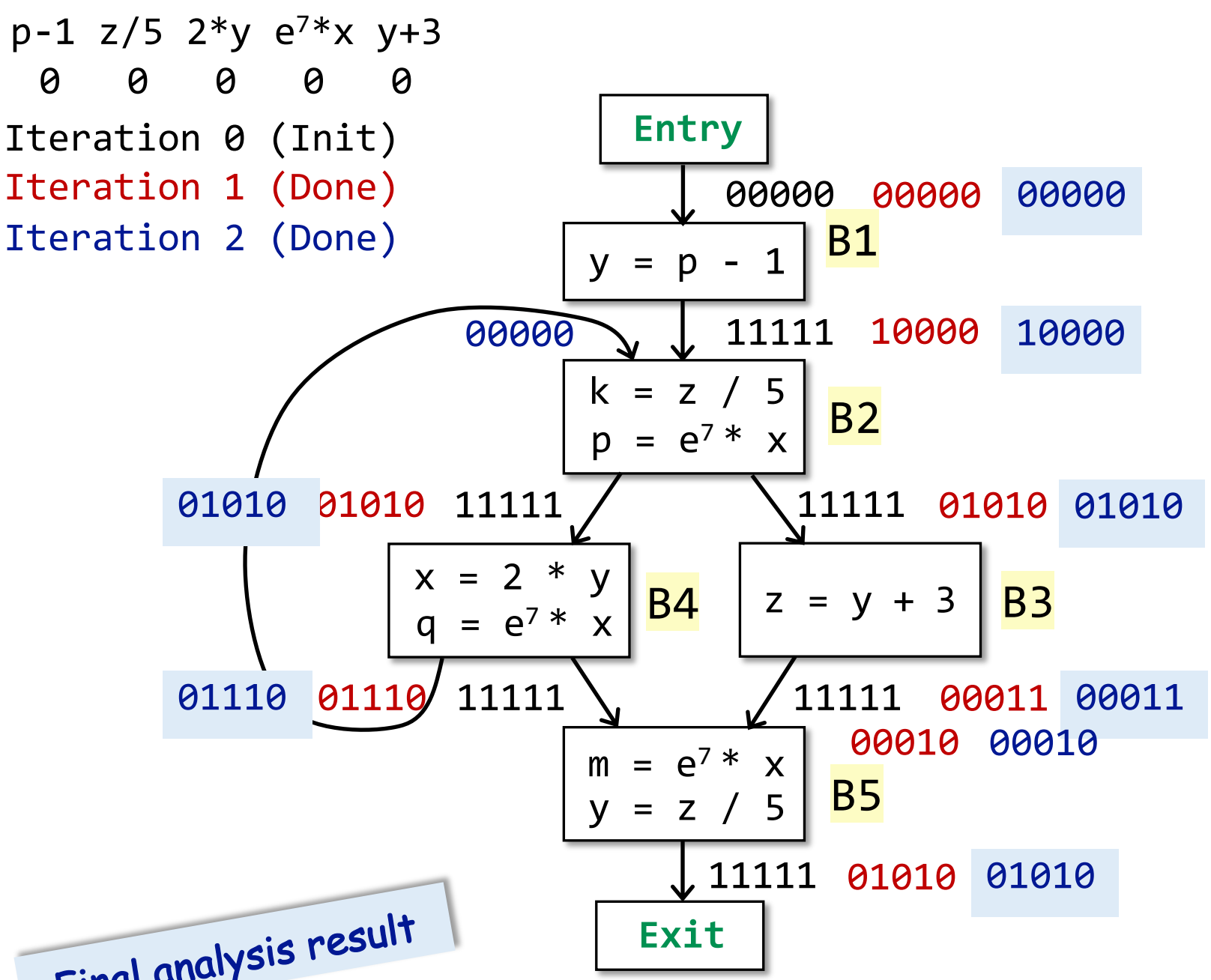
Iteration 0 (Init)

Iteration 1 (Done)

Iteration 2 (Done)



No changes occur in any OUT[]


p-1 z/5 2*y e7*x y+3
0 0 0 0 0
Iteration 0 (Init)
Iteration 1 (Done)
Iteration 2 (Done)
Entry
00000 00000 00000
y = p - 1
B1
00000
11111 10000 10000
k = z / 5
p = e7 * x
B2
01010 01010 11111
11111 01010 01010
x = 2 * y
q = e7 * x
B4
z = y + 3
B3
01110 01110 11111
11111 00011 00011
00010 00010
m = e7 * x
y = z / 5
B5
11111 01010 01010
Exit
Final analysis result

Analysis Comparison

	Reaching Definitions	Live Variables	Available Expressions
Domain			
Direction			
May/Must			
Boundary			
Initialization			
Transfer function			
Meet			

Analysis Comparison

	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction			
May/Must			
Boundary			
Initialization			
Transfer function			
Meet			

Analysis Comparison

	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction	Forwards	Backwards	Forwards
May/Must			
Boundary			
Initialization			
Transfer function			
Meet			

Analysis Comparison

	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction	Forwards	Backwards	Forwards
May/Must	May	May	Must
Boundary			
Initialization			
Transfer function			
Meet			

Analysis Comparison

	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction	Forwards	Backwards	Forwards
May/Must	May	May	Must
Boundary	OUT[entry] = ∅	IN[exit] = ∅	OUT[entry] = ∅
Initialization			
Transfer function			
Meet			

Analysis Comparison

	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction	Forwards	Backwards	Forwards
May/Must	May	May	Must
Boundary	OUT[entry] = ∅	IN[exit] = ∅	OUT[entry] = ∅
Initialization	OUT[B] = ∅	IN[B] = ∅	OUT[B] = U
Transfer function			
Meet			

Analysis Comparison

	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction	Forwards	Backwards	Forwards
May/Must	May	May	Must
Boundary	OUT[entry] = ∅	IN[exit] = ∅	OUT[entry] = ∅
Initialization	OUT[B] = ∅	IN[B] = ∅	OUT[B] = U
Transfer function	OUT/IN = gen U (IN/OUT - kill)		
Meet			

Analysis Comparison

	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction	Forwards	Backwards	Forwards
May/Must	May	May	Must
Boundary	OUT[entry] = ∅	IN[exit] = ∅	OUT[entry] = ∅
Initialization	OUT[B] = ∅	IN[B] = ∅	OUT[B] = U
Transfer function	OUT/IN = gen U (IN/OUT - kill)		
Meet	U	U	∩

Analysis Comparison

According to the meaning of the analysis

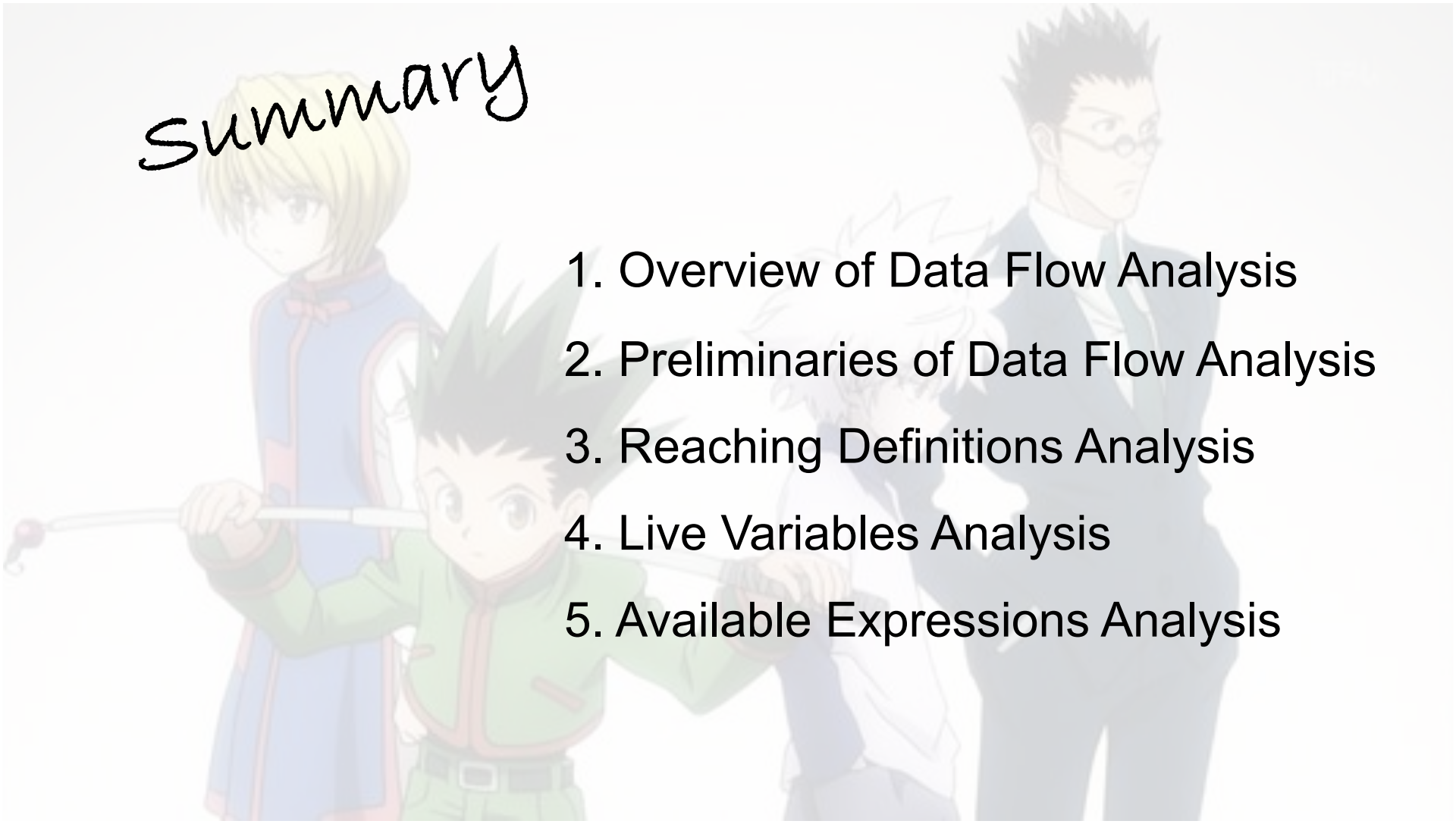
	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction	Forwards	Backwards	Forwards
May/Must	May	May	Must
Boundary	OUT[entry] = ∅	IN[exit] = ∅	OUT[entry] = ∅
Initialization	OUT[B] = ∅	IN[B] = ∅	OUT[B] = U
Transfer function	OUT/IN = gen U (IN/OUT - kill)		
Meet	U	U	∩

Analysis Comparison

According to the meaning of the analysis
We'll draw a theoretical framework to systematically explain them in next lectures

	Reaching Definitions	Live Variables	Available Expressions
Domain	Set of definitions	Set of variables	Set of expressions
Direction	Forwards	Backwards	Forwards
May/Must	May	May	Must
Boundary	OUT[entry] = ∅	IN[exit] = ∅	OUT[entry] = ∅
Initialization	OUT[B] = ∅	IN[B] = ∅	OUT[B] = U
Transfer function	OUT/IN = gen U (IN/OUT - kill)		
Meet	U	U	∩

Summary



1. Overview of Data Flow Analysis
2. Preliminaries of Data Flow Analysis
3. Reaching Definitions Analysis
4. Live Variables Analysis
5. Available Expressions Analysis

The X You Need To Understand in This Lecture

- Understand the three data flow analyses:
  - reaching definitions
  - live variables
  - available expressions
- Can tell the differences and similarities of the three data flow analyses
- Understand the iterative algorithm and can tell why it is able to terminate

Assignment One:
Live variable analysis and iterative solver

Evaluation Criteria

- Coding Assignments 40% http://tai-e.pascal-lab.net
- Final Exam 60%

OJ注意事项：

- 用学校邮箱注册
- 填写Student ID
- Nickname用真实姓名
- 抄袭：第一次发现，该次作业0分
  第二次发现，课程0分
- 不交：得5%诚信分
- 迟交：扣得分5% x D, D为迟交天数
- 每帮助找出1个新的有效test case，实验分数+1