Latest Advancements in Automatic Vectorization Research

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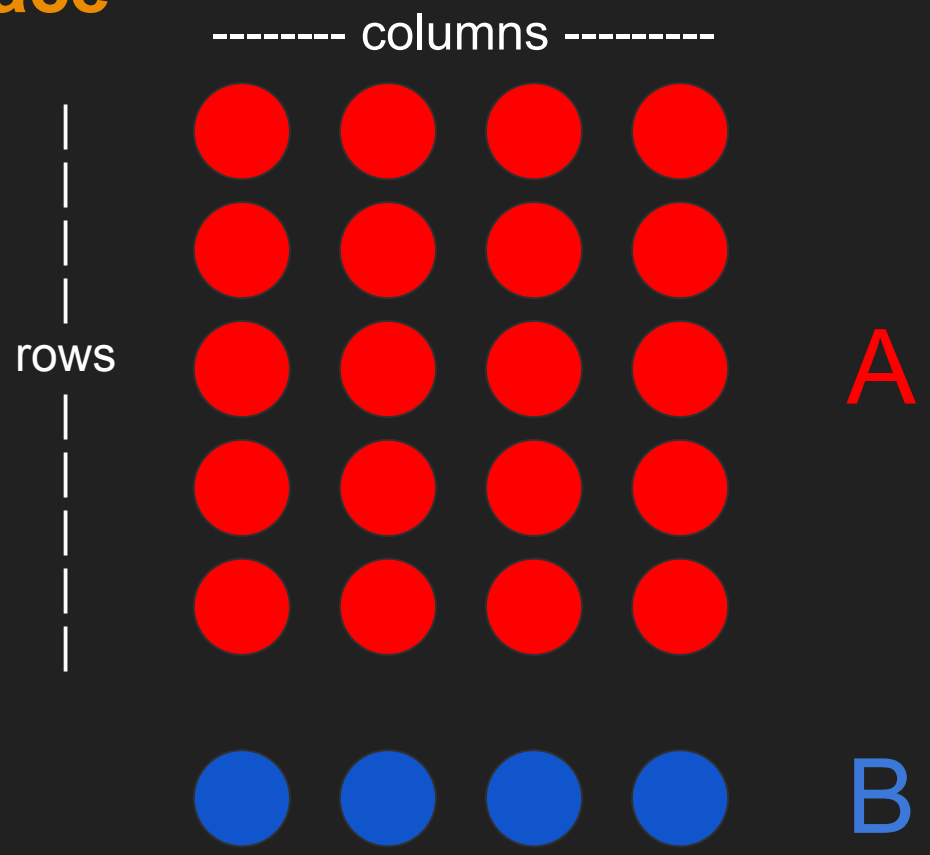
LLVM ❤ Compilers Research

Sum Columns Original

```
for (int i = 0; i < n; ++i) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Memory Space



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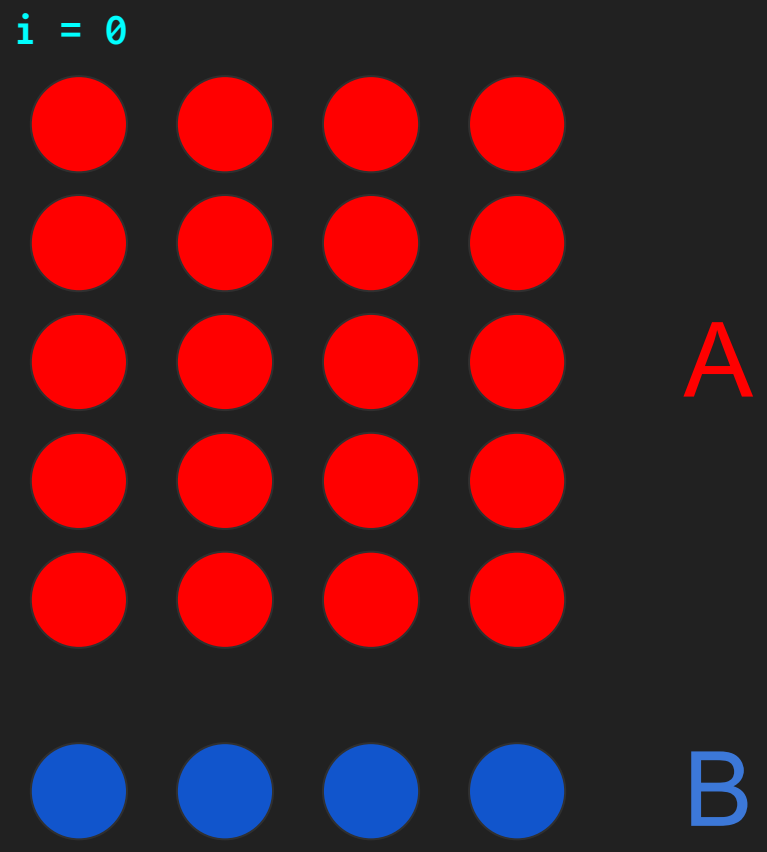

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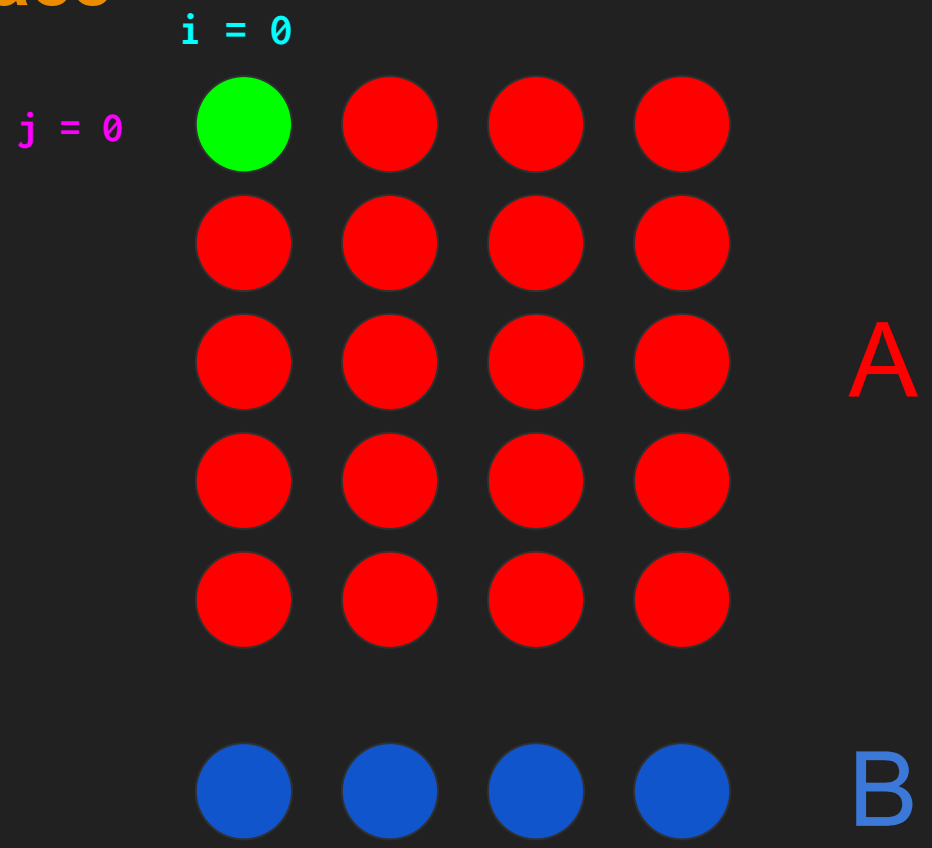

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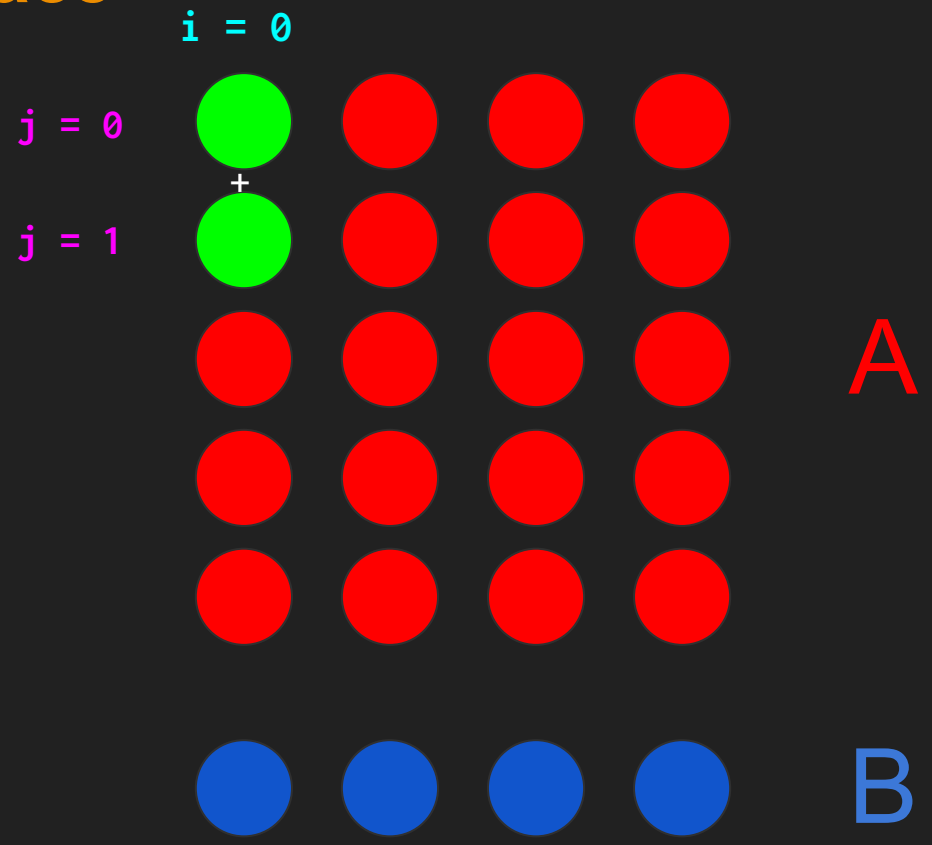

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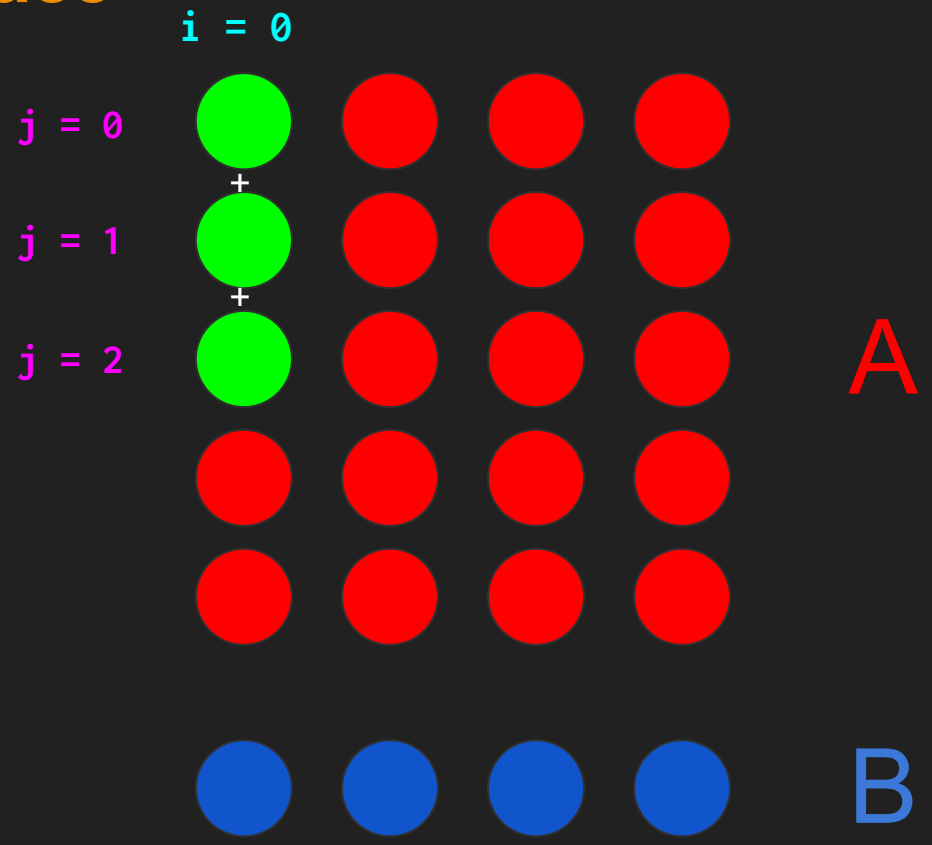

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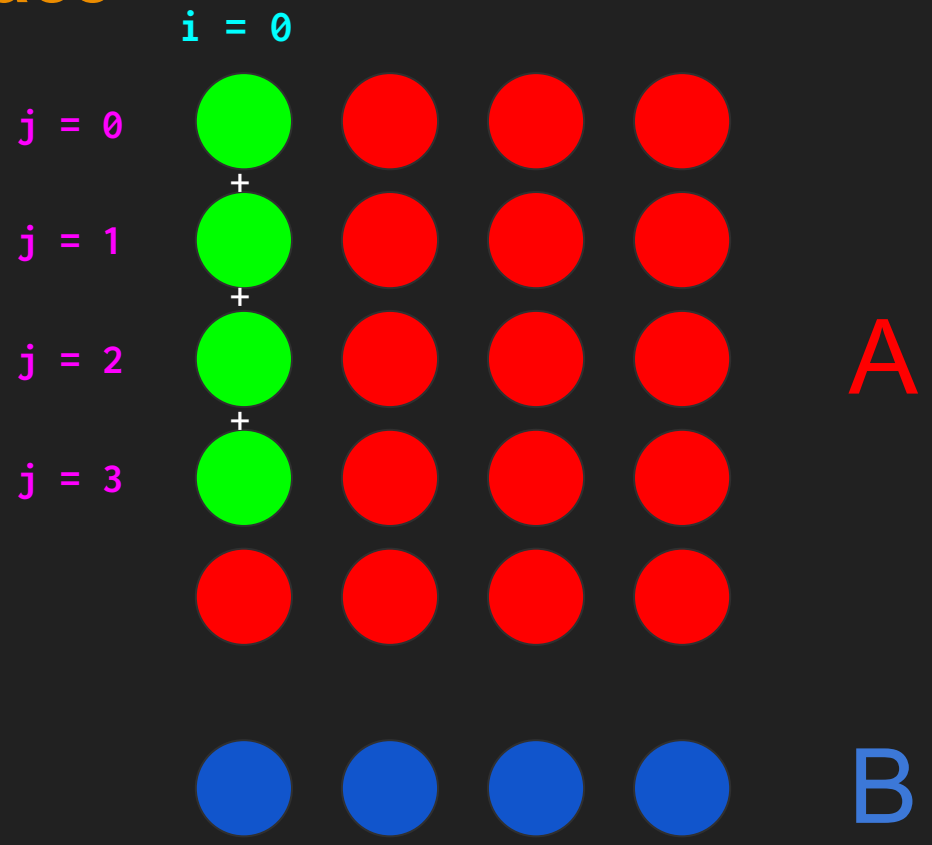

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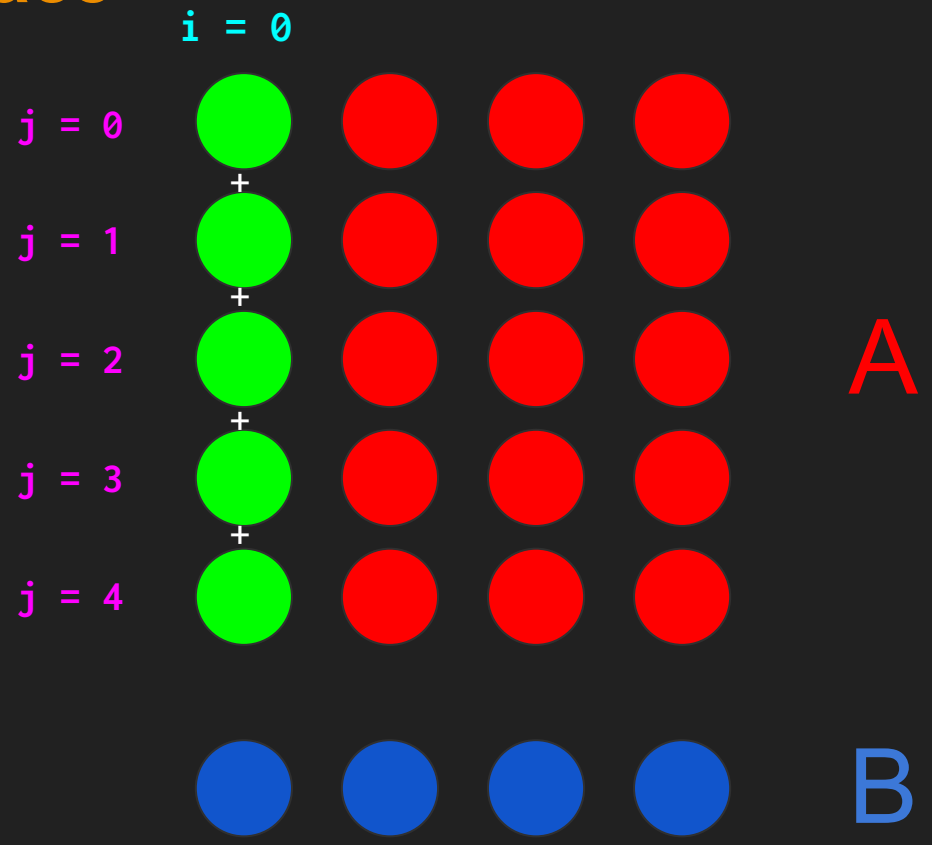

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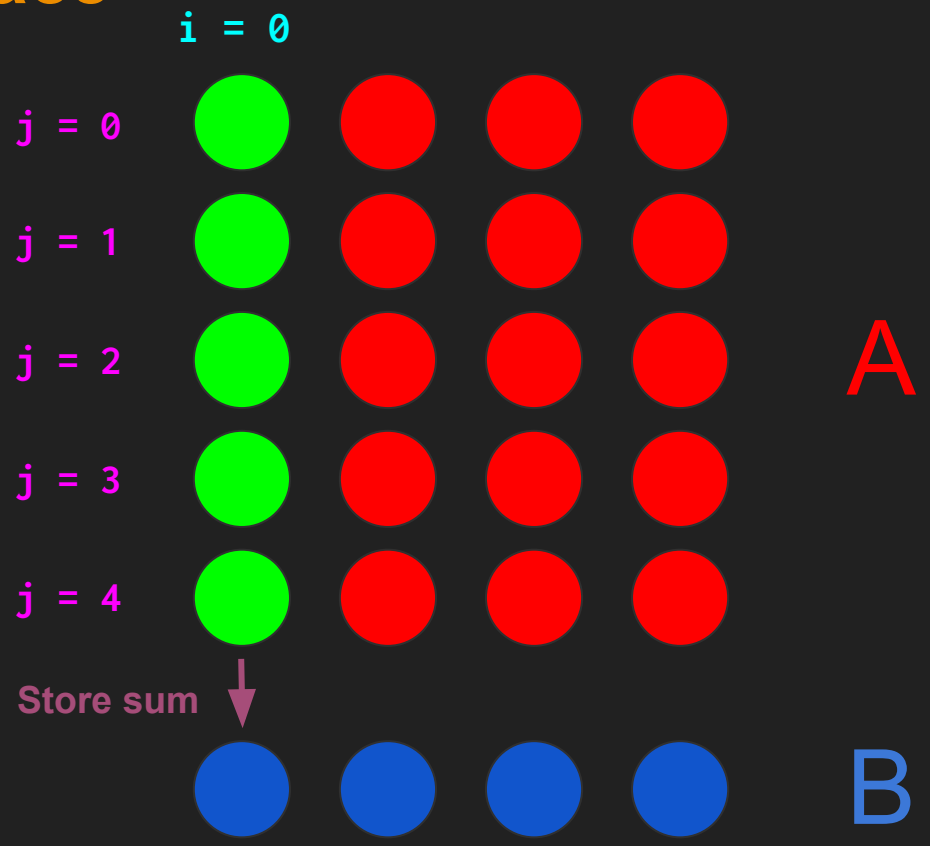

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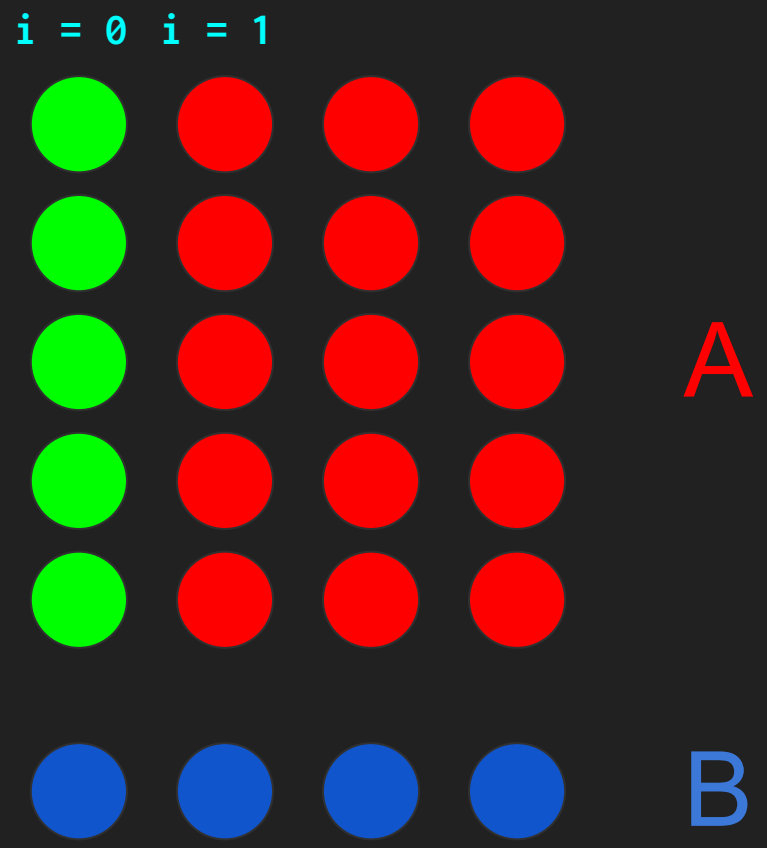

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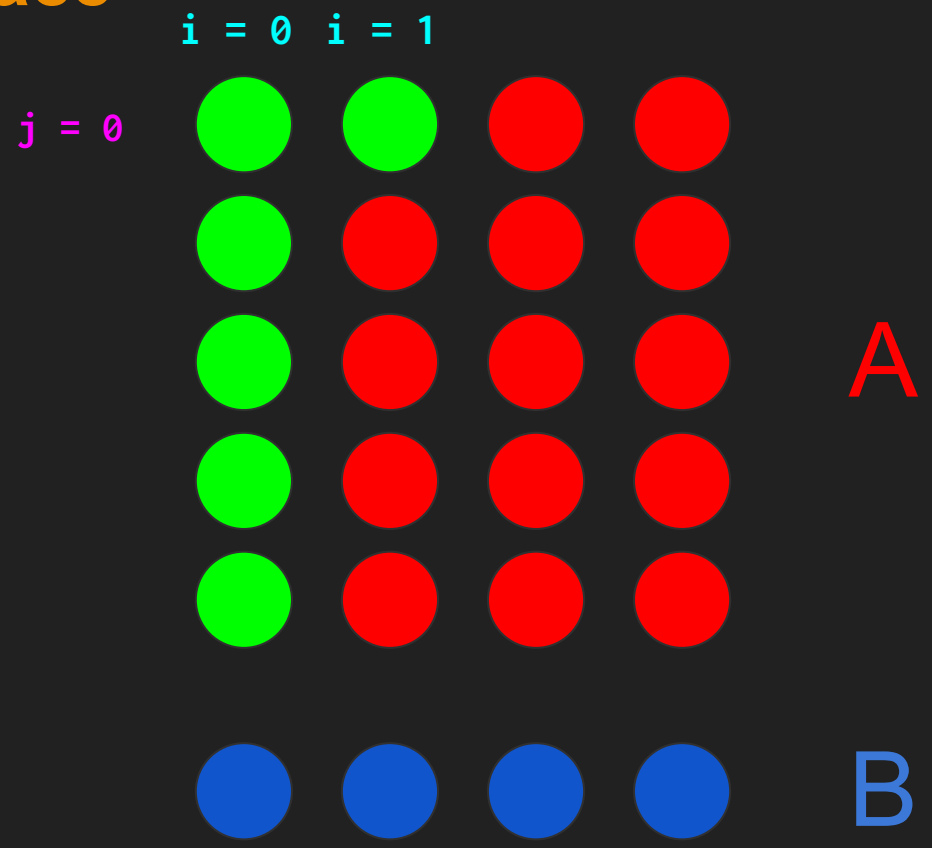

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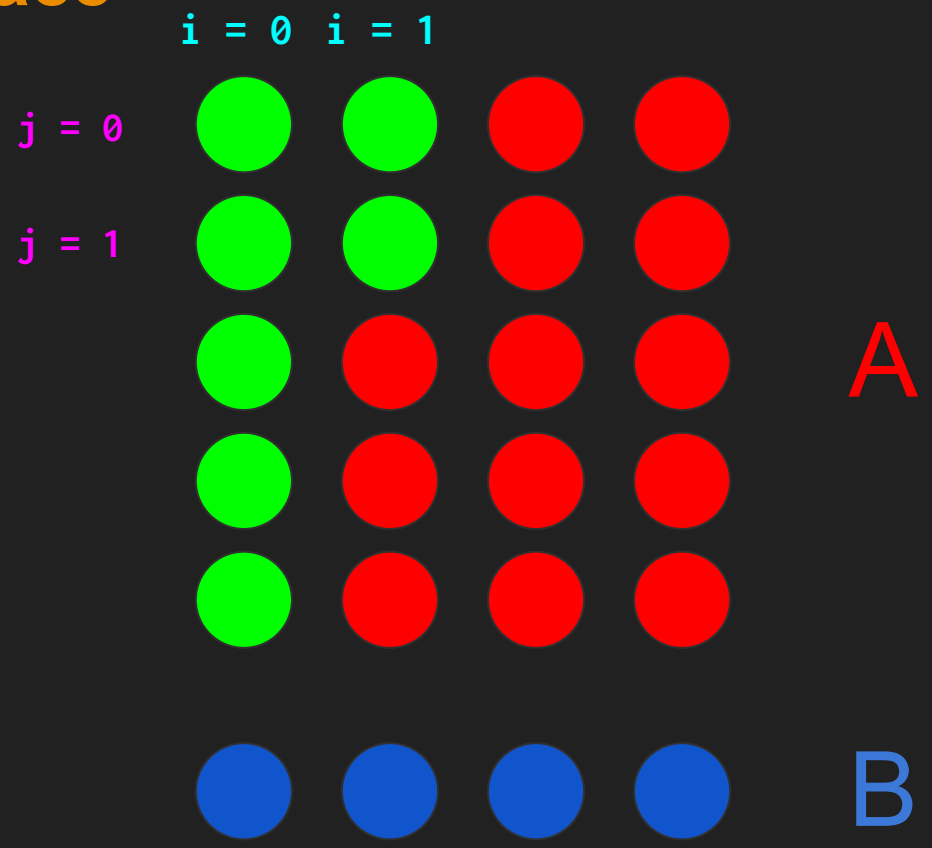
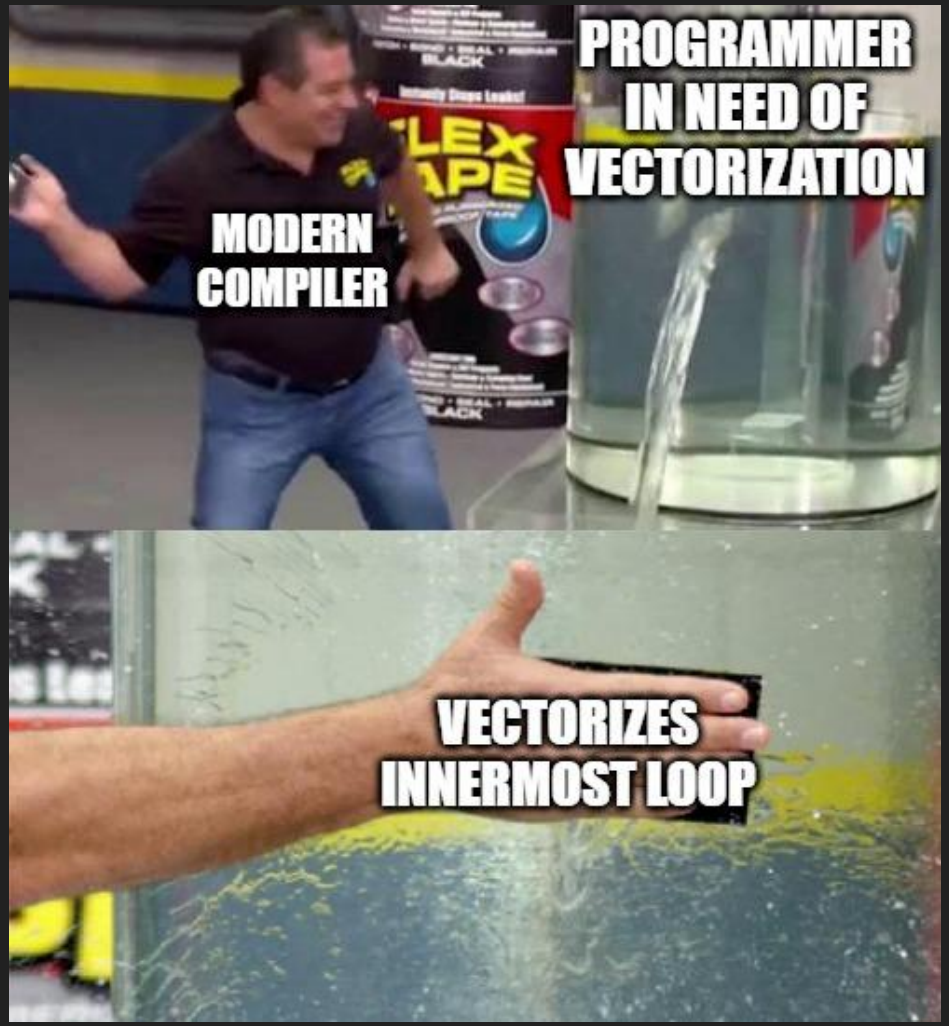


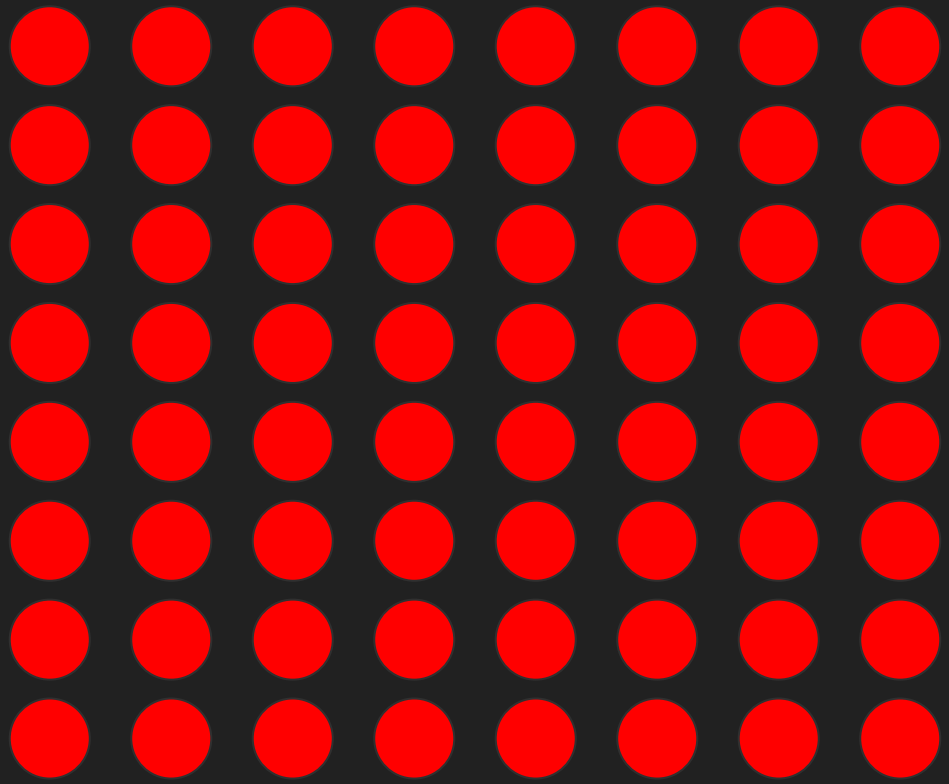

I WANT
VECTORIZATION


MODERN COMPILER
PROGRAMMER IN NEED OF VECTORIZATION
VECTORIZES INNERMOST LOOP

Sum Columns Original

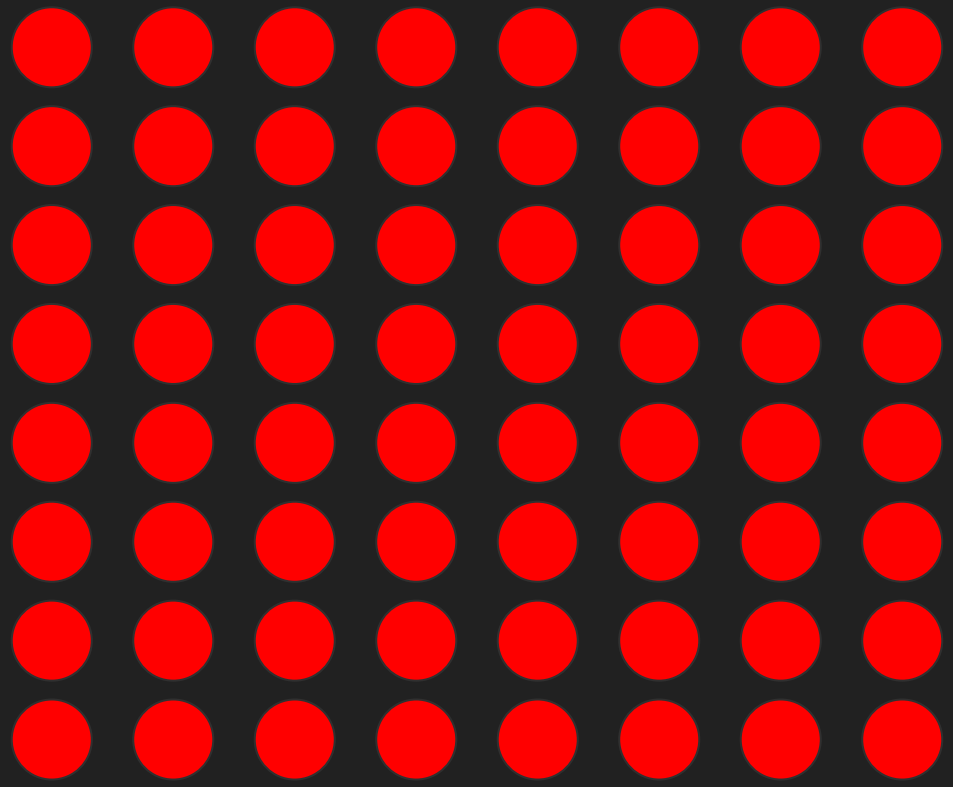
```
for (int i = 0; i < n; ++i) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Memory Space



Memory Space

i = 0



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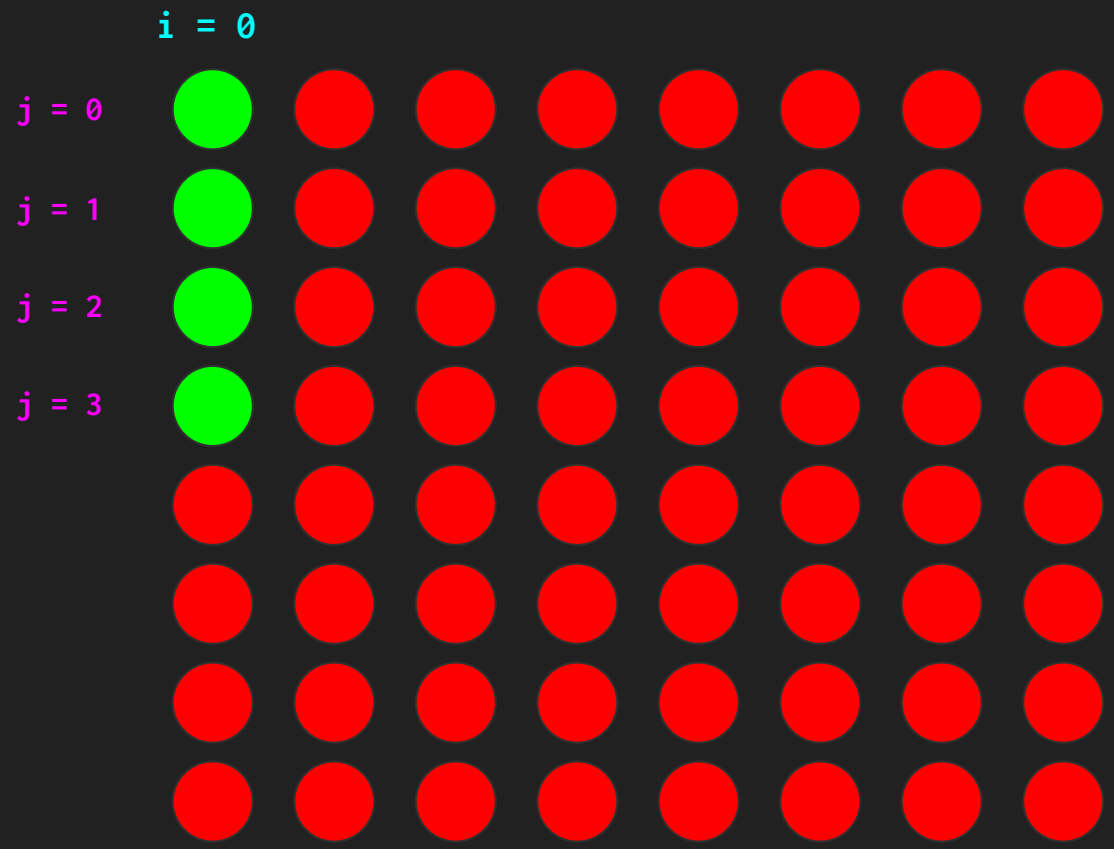
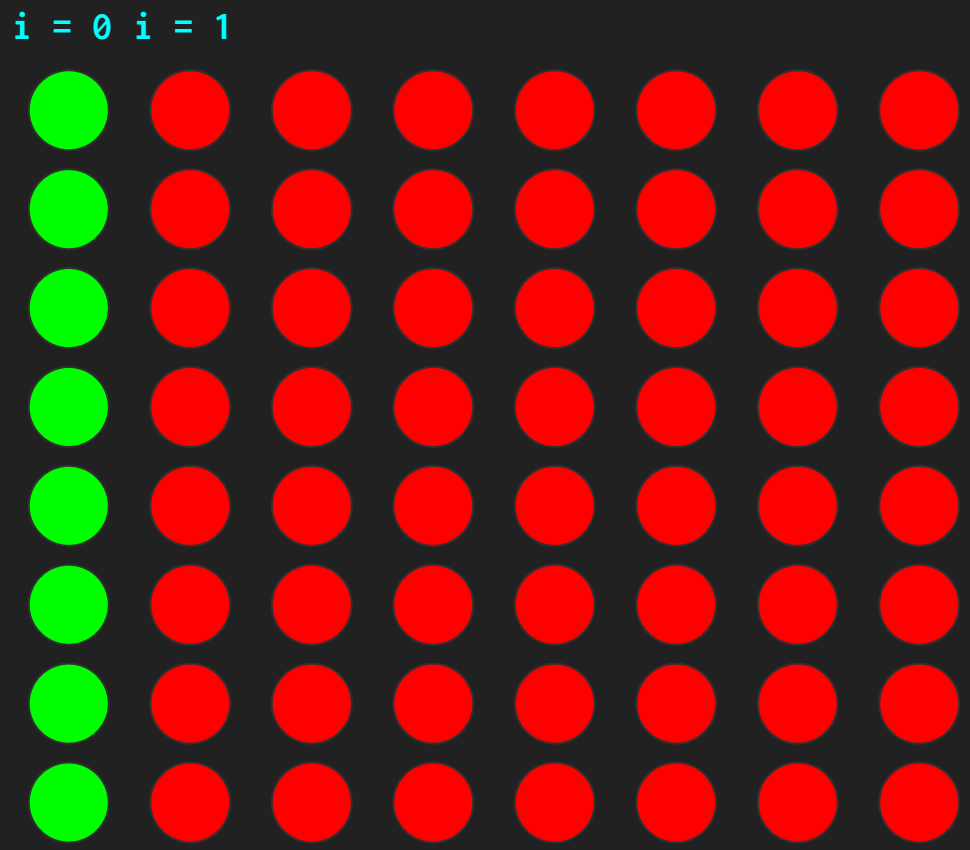


Memory Space

Memory Space



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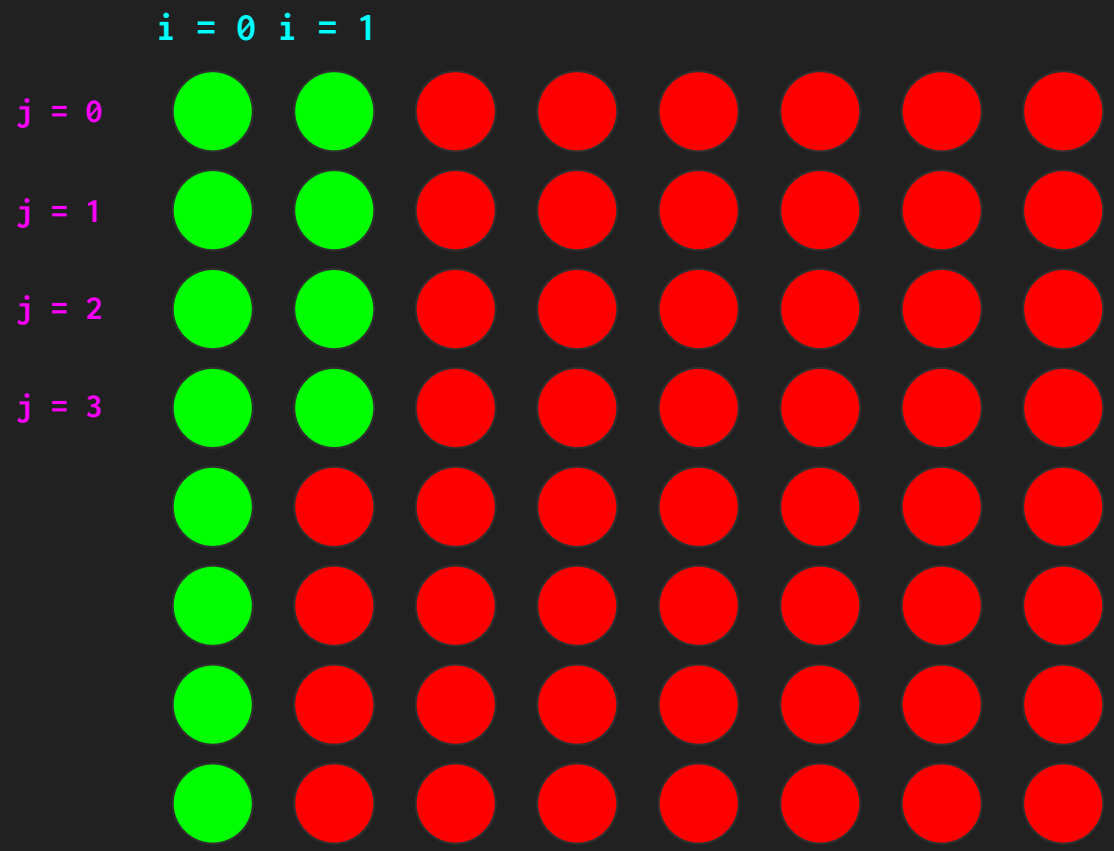

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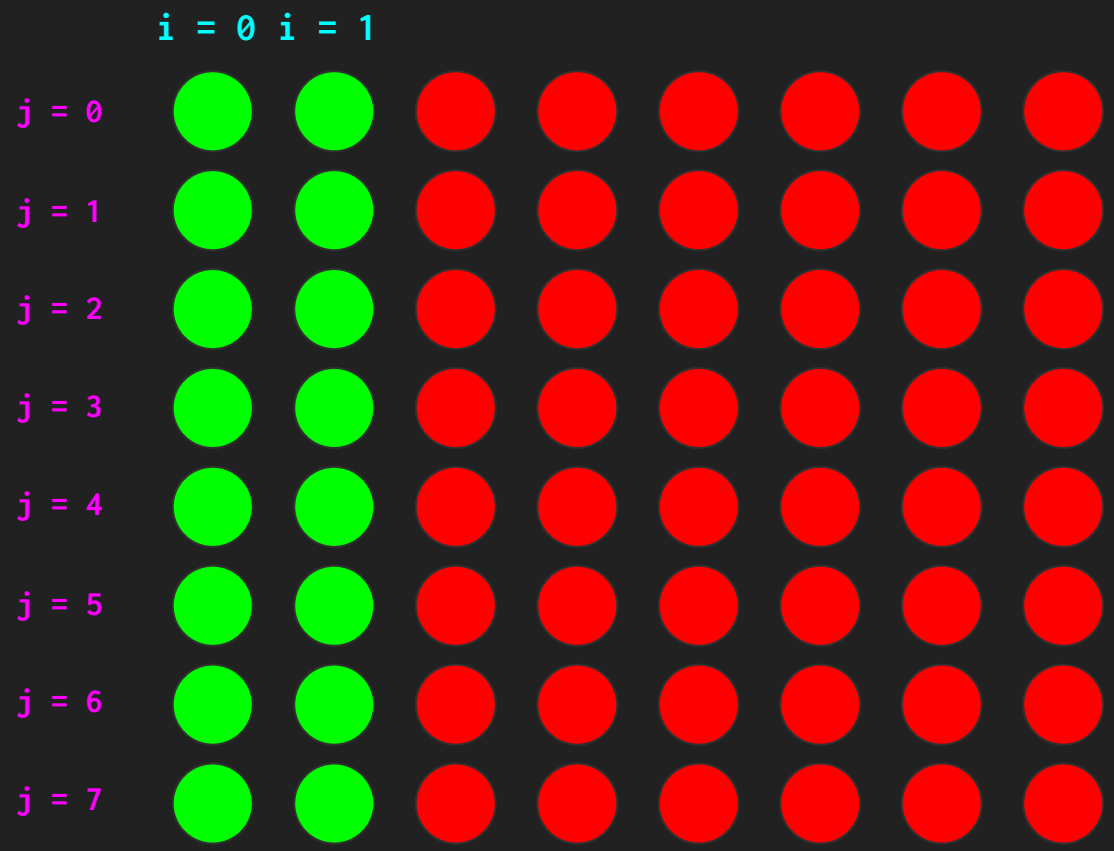

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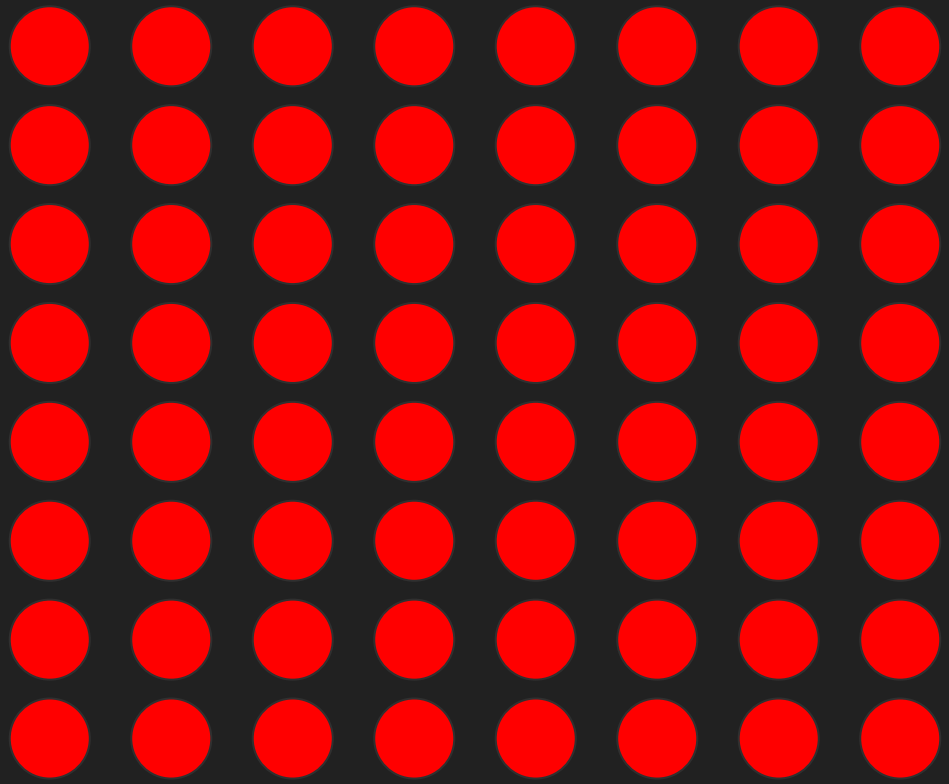

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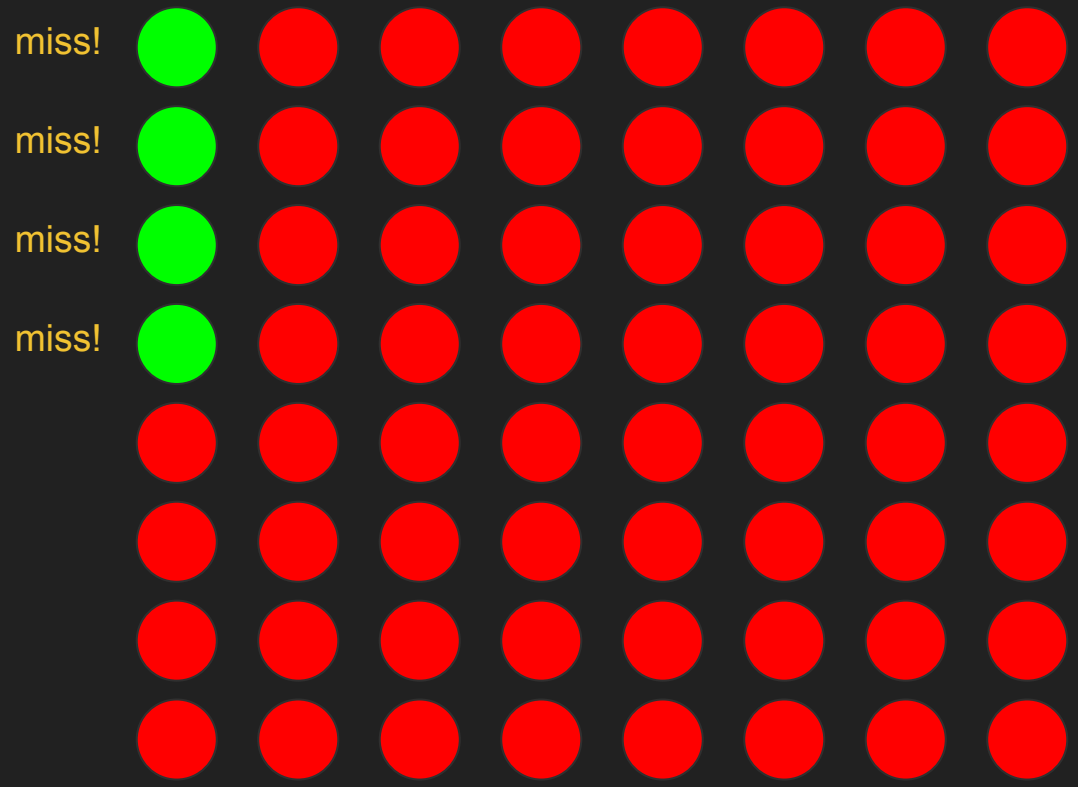

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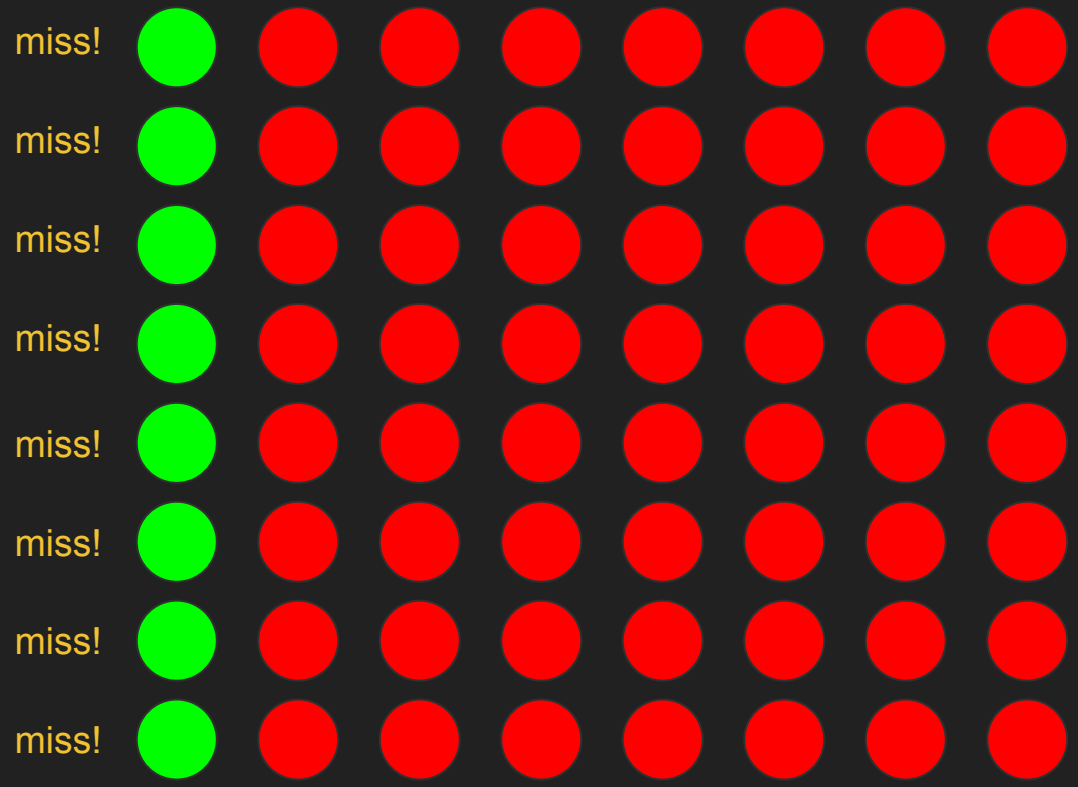

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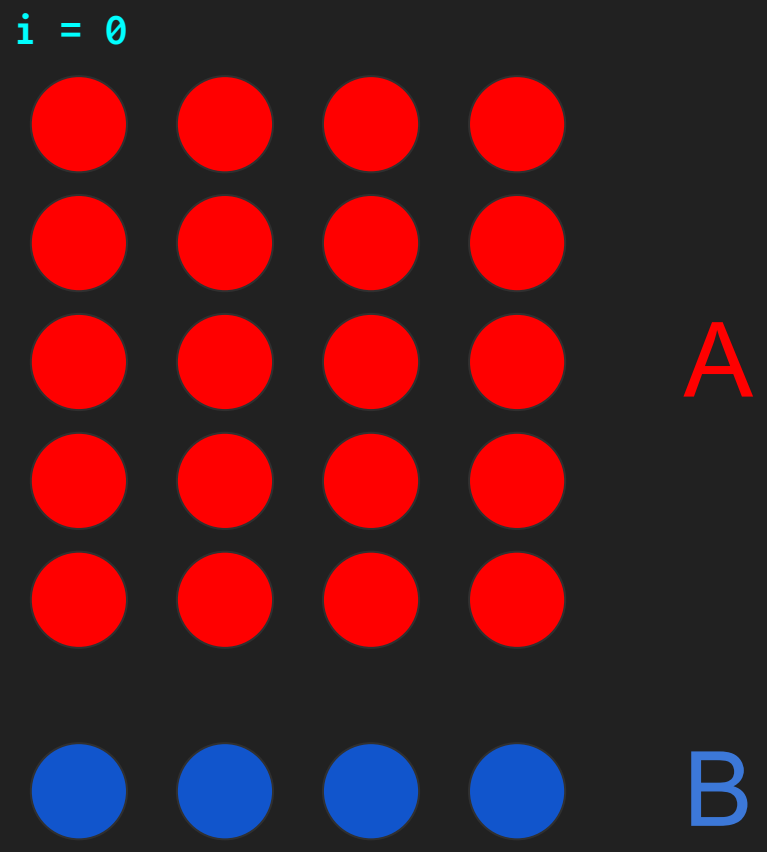

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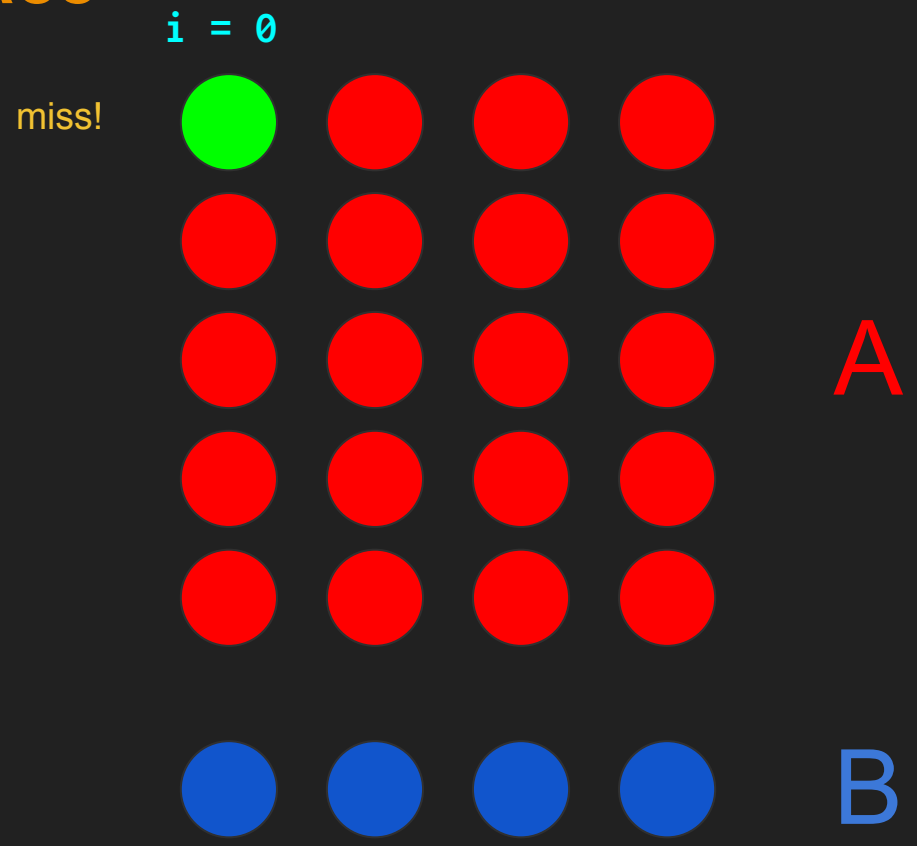

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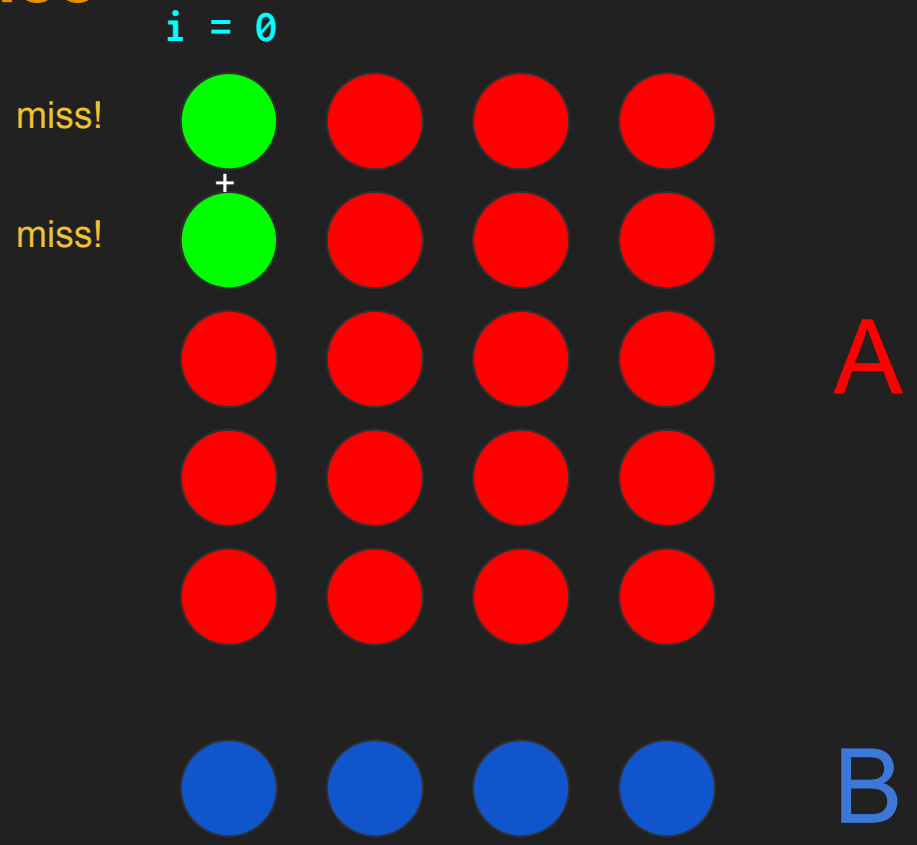

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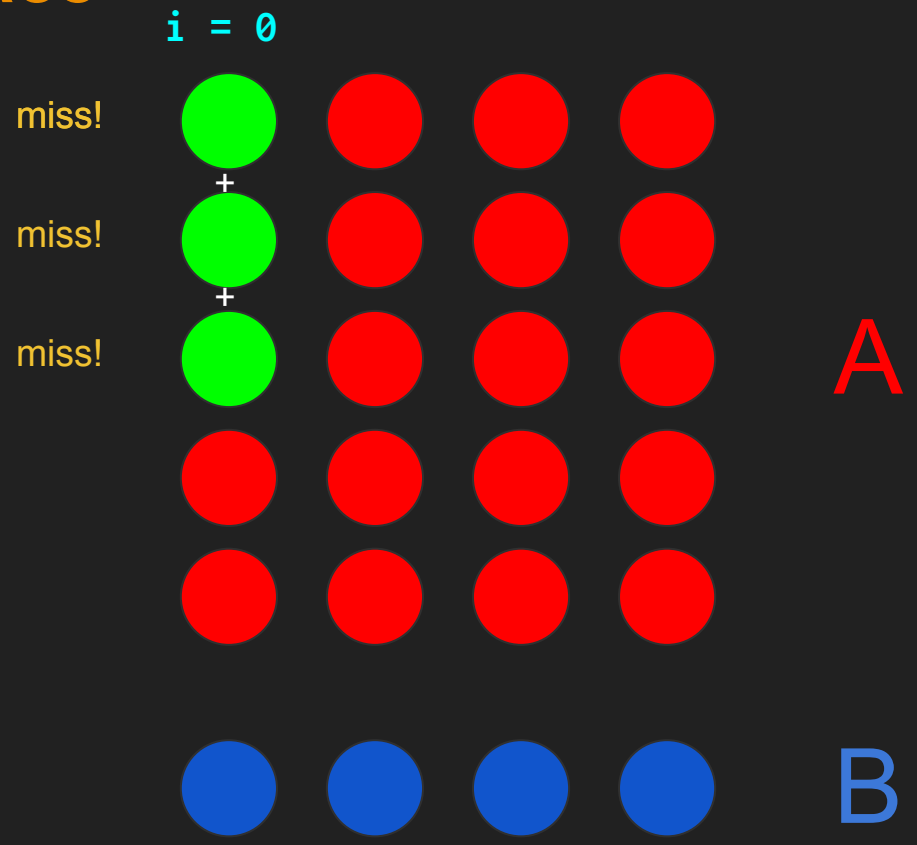

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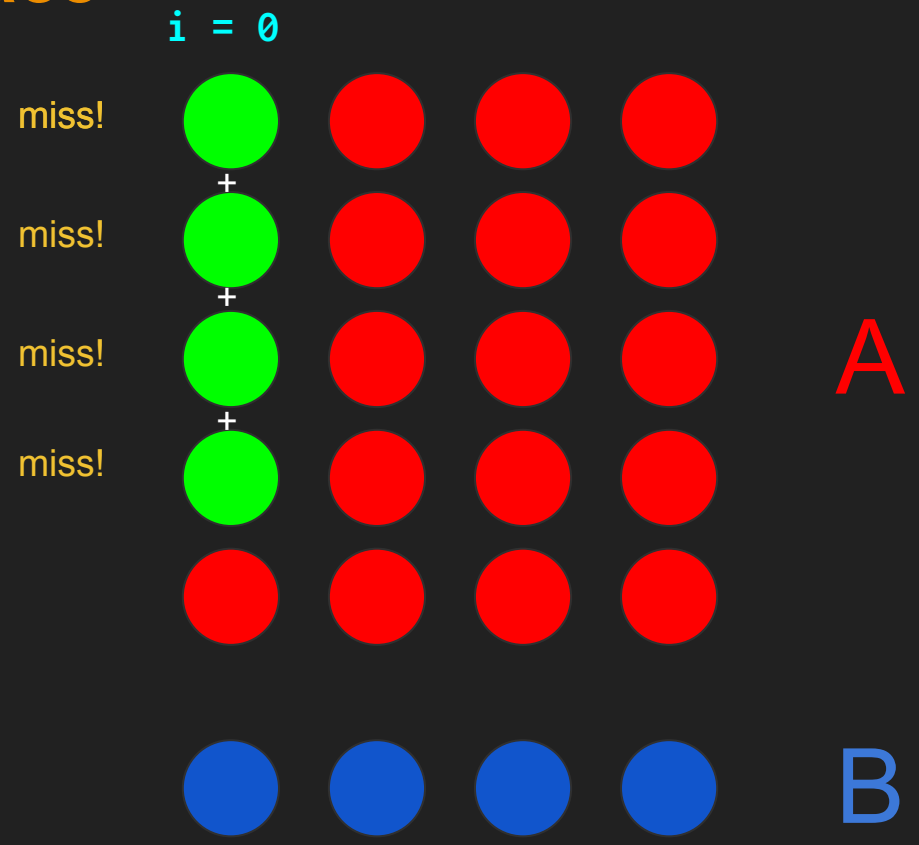

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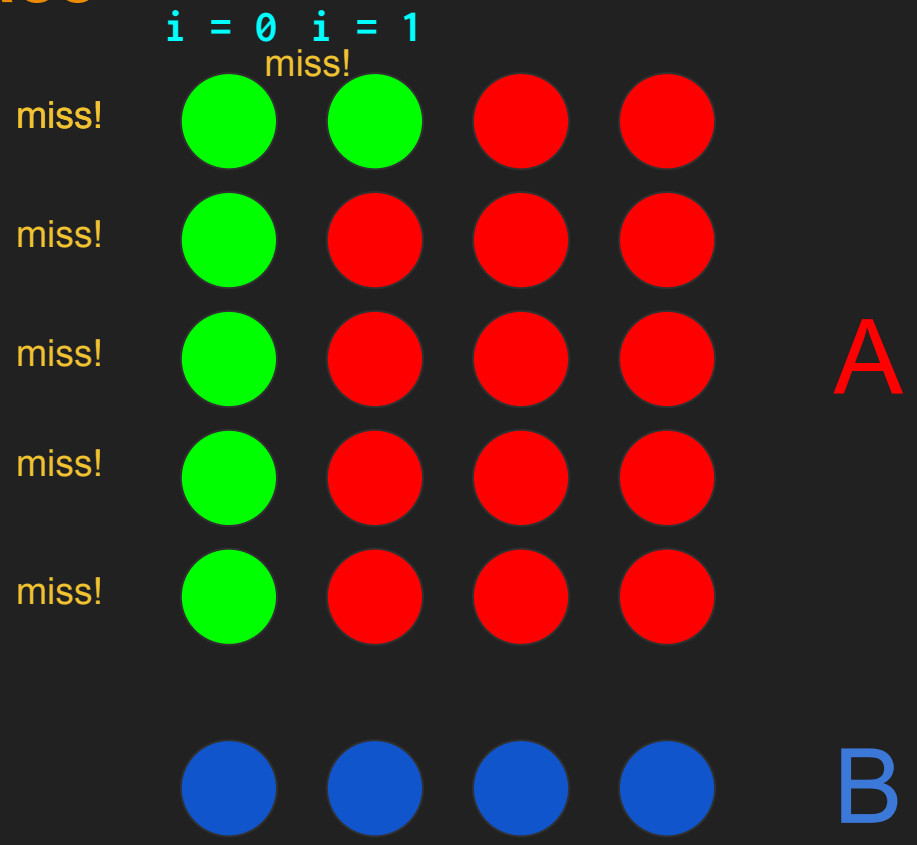

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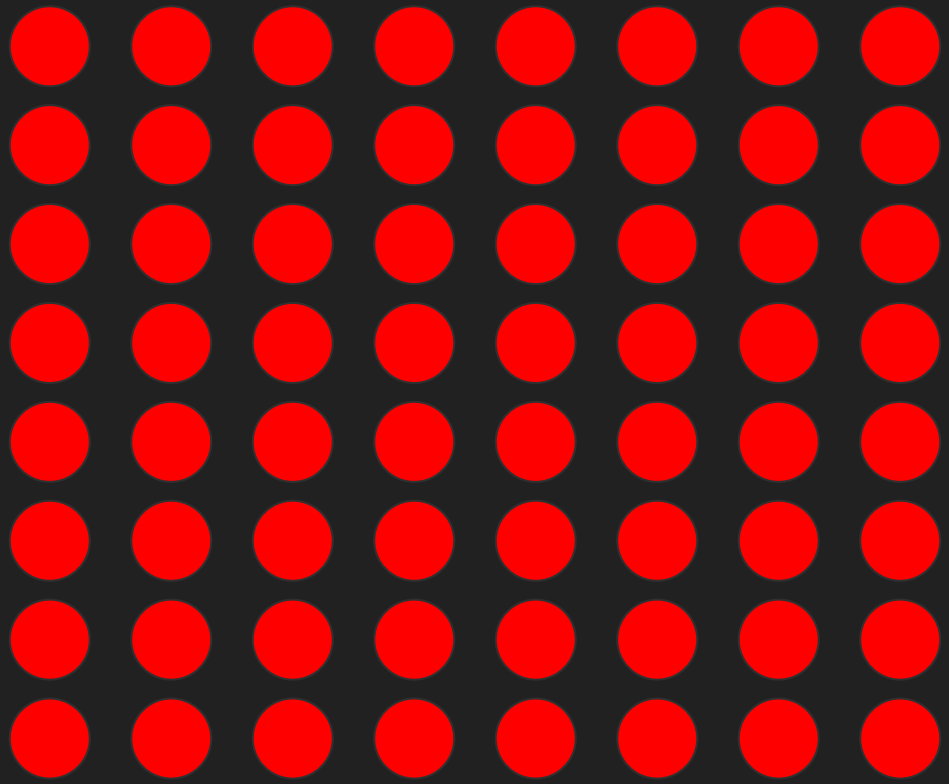

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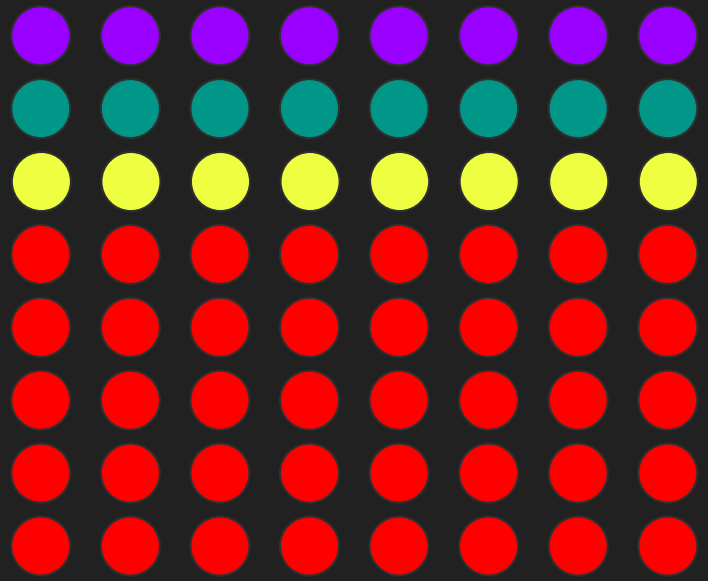

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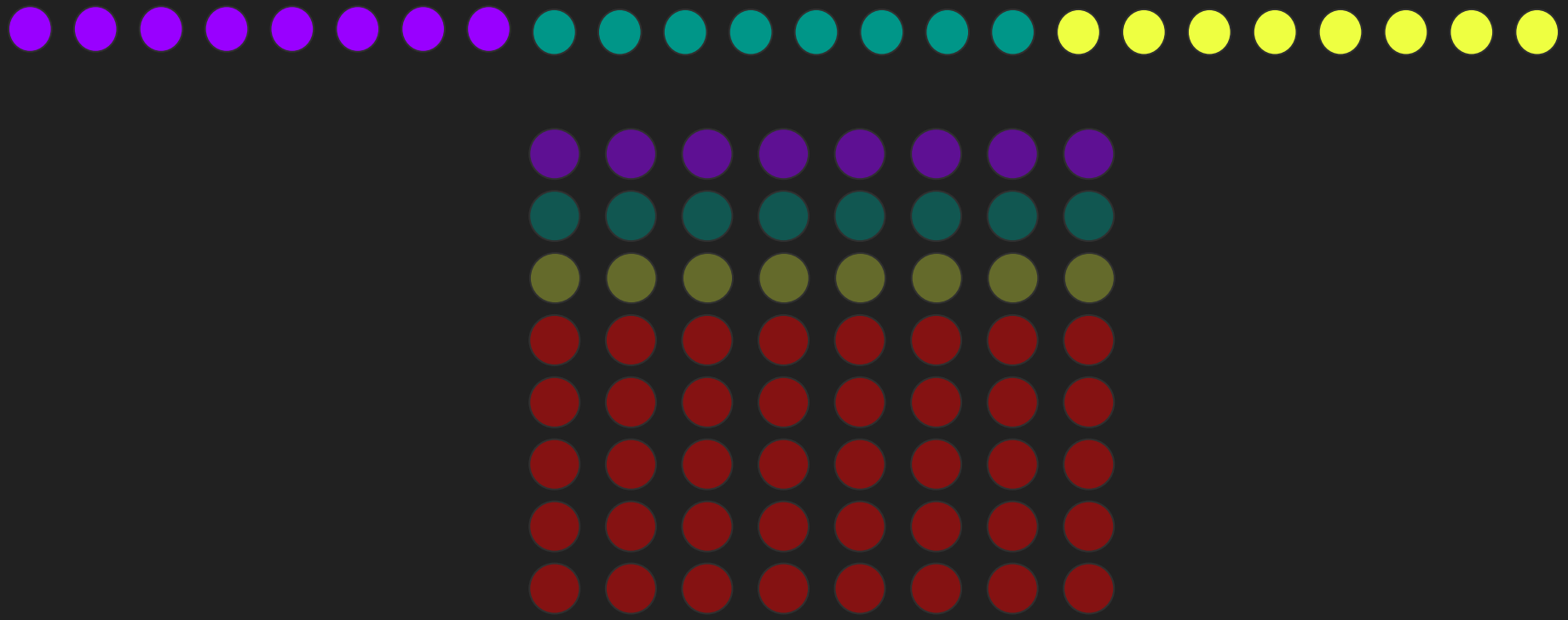

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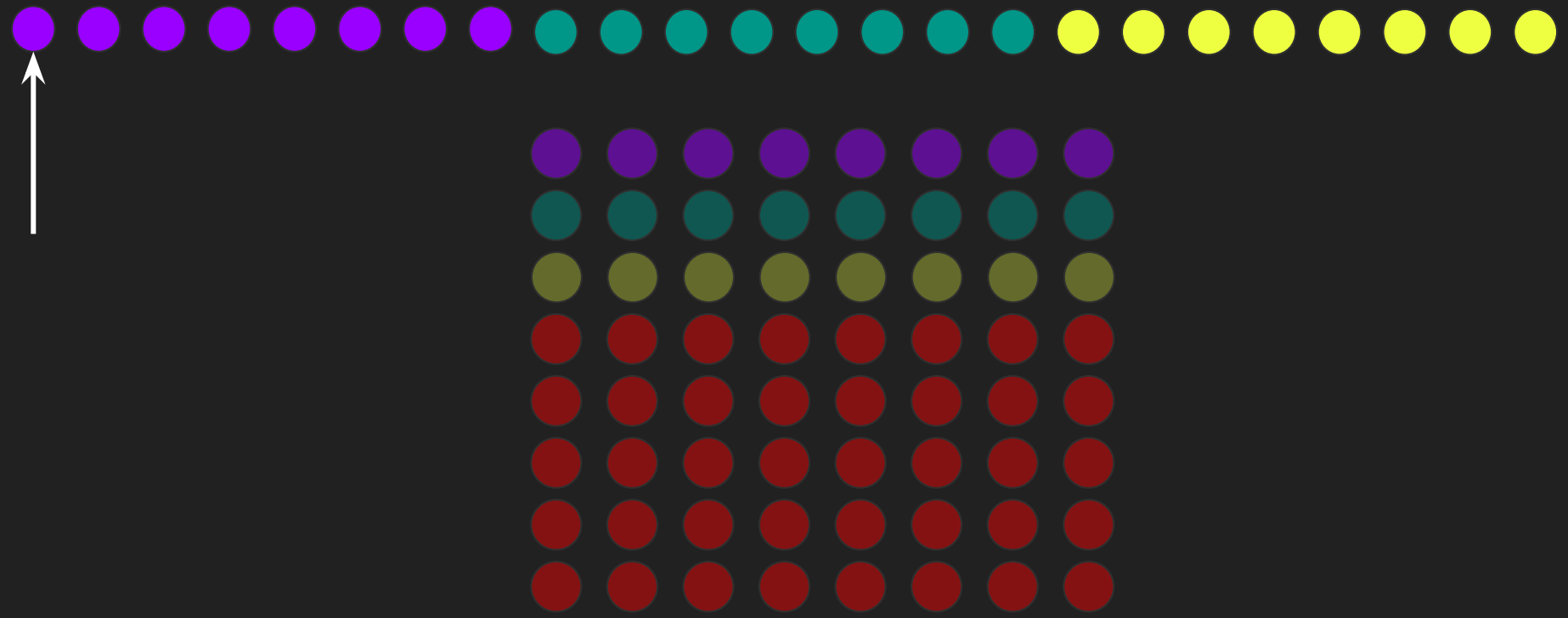

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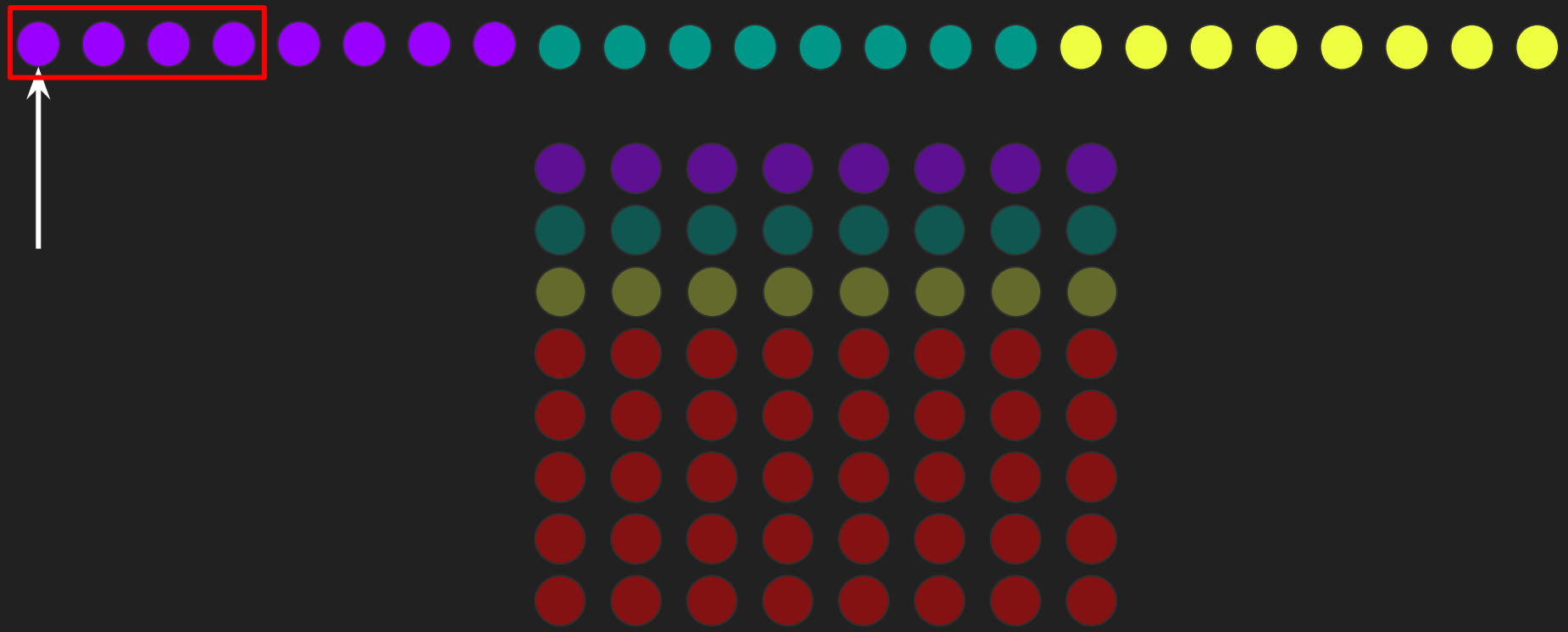
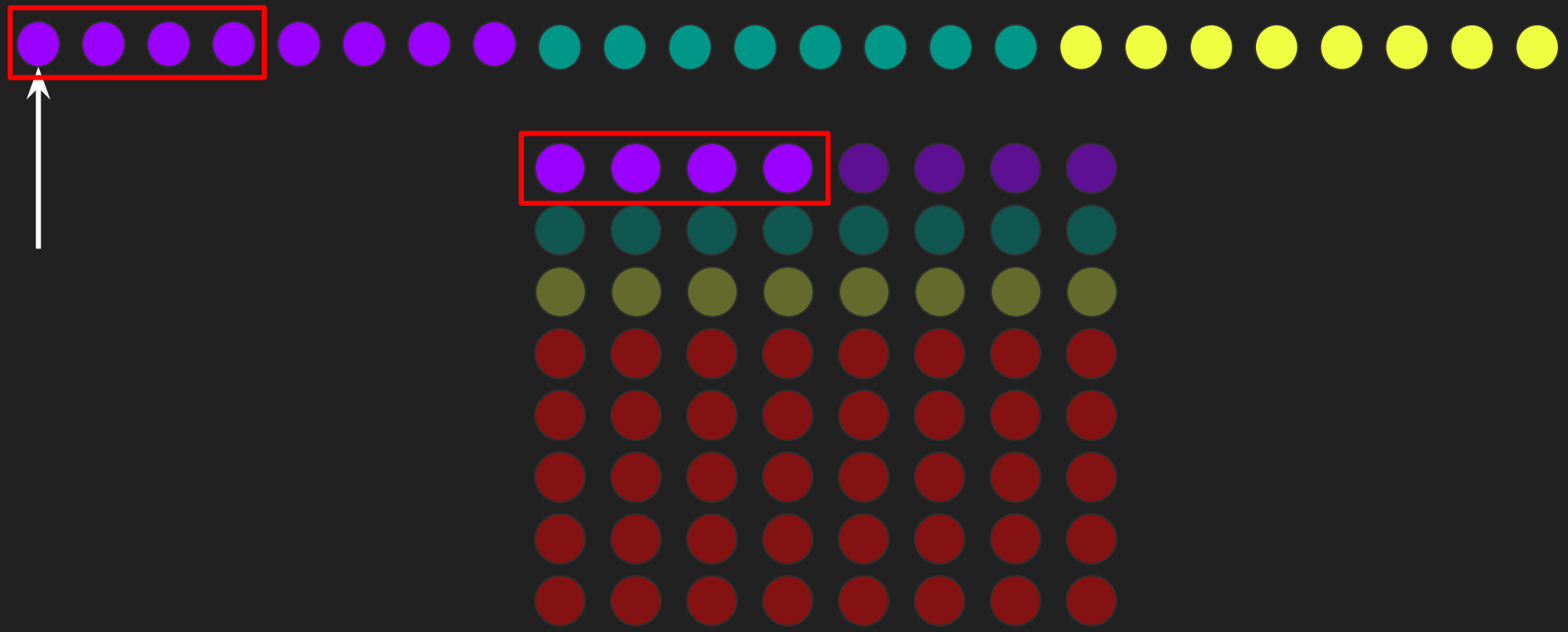


Memory Space



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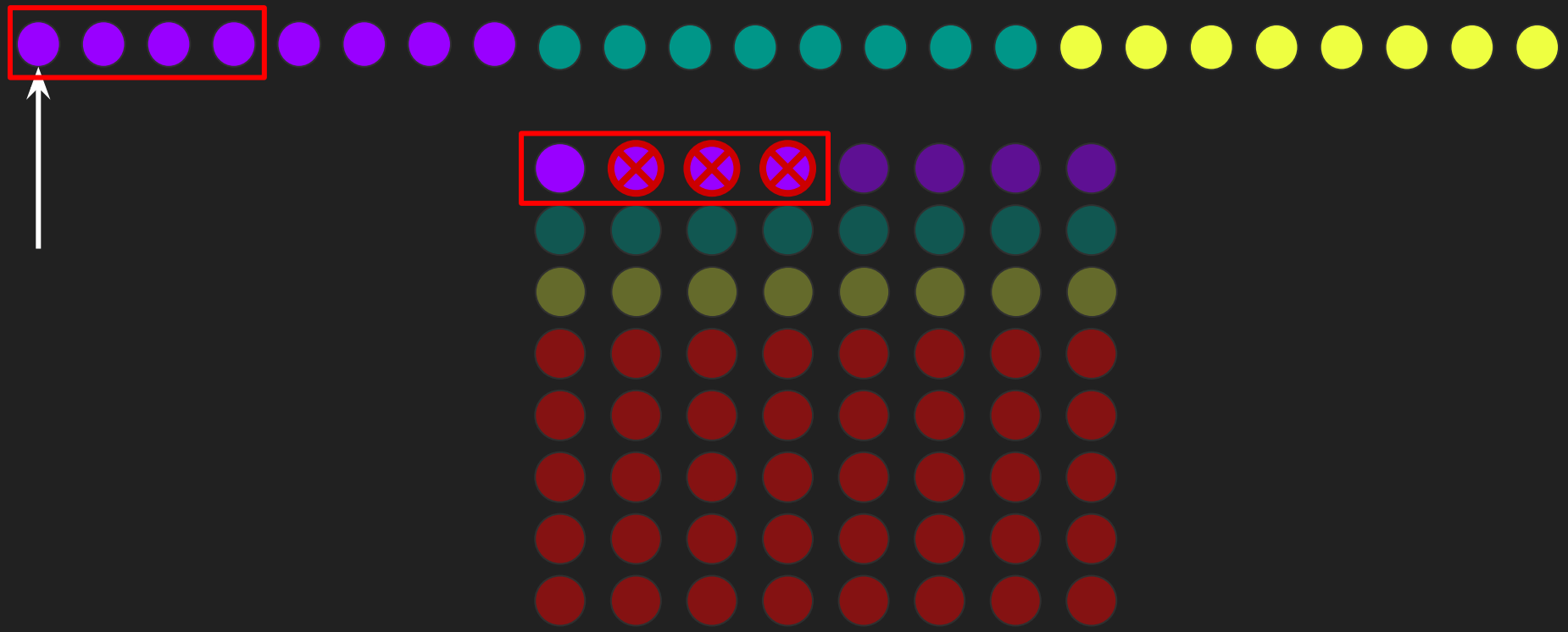

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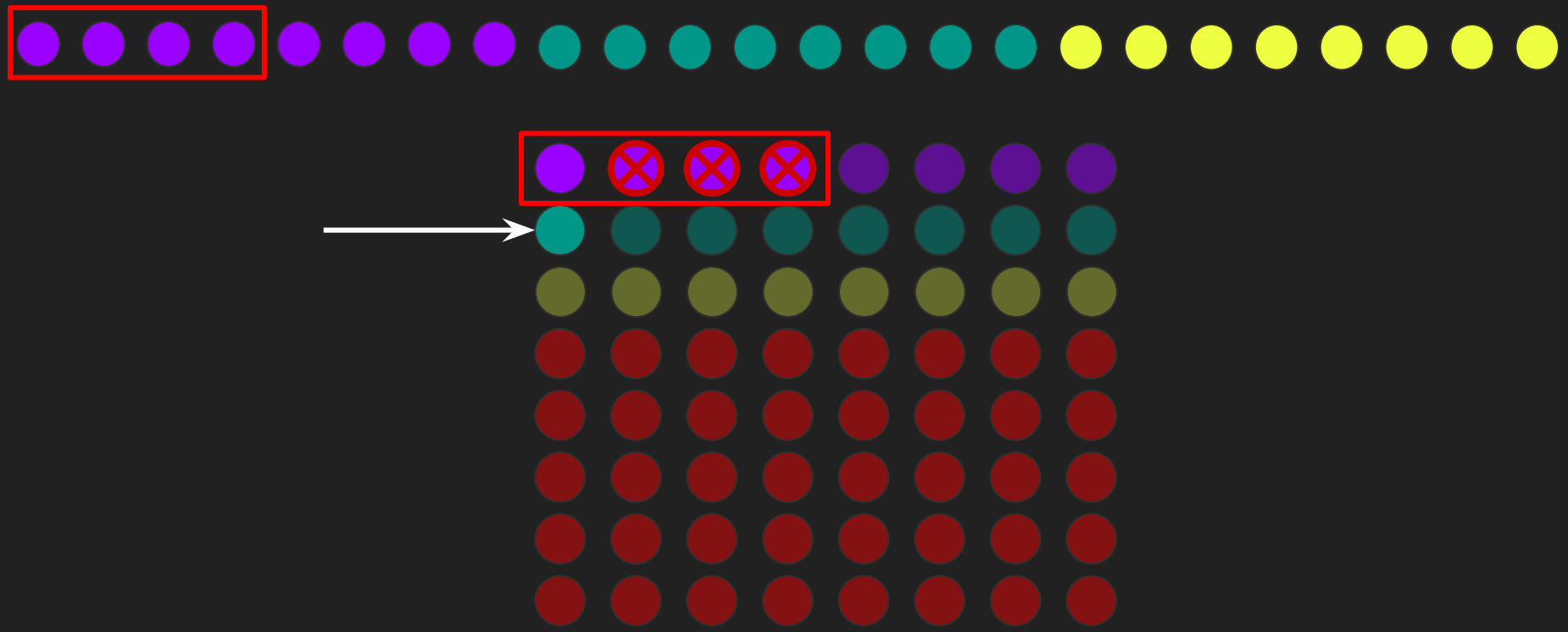

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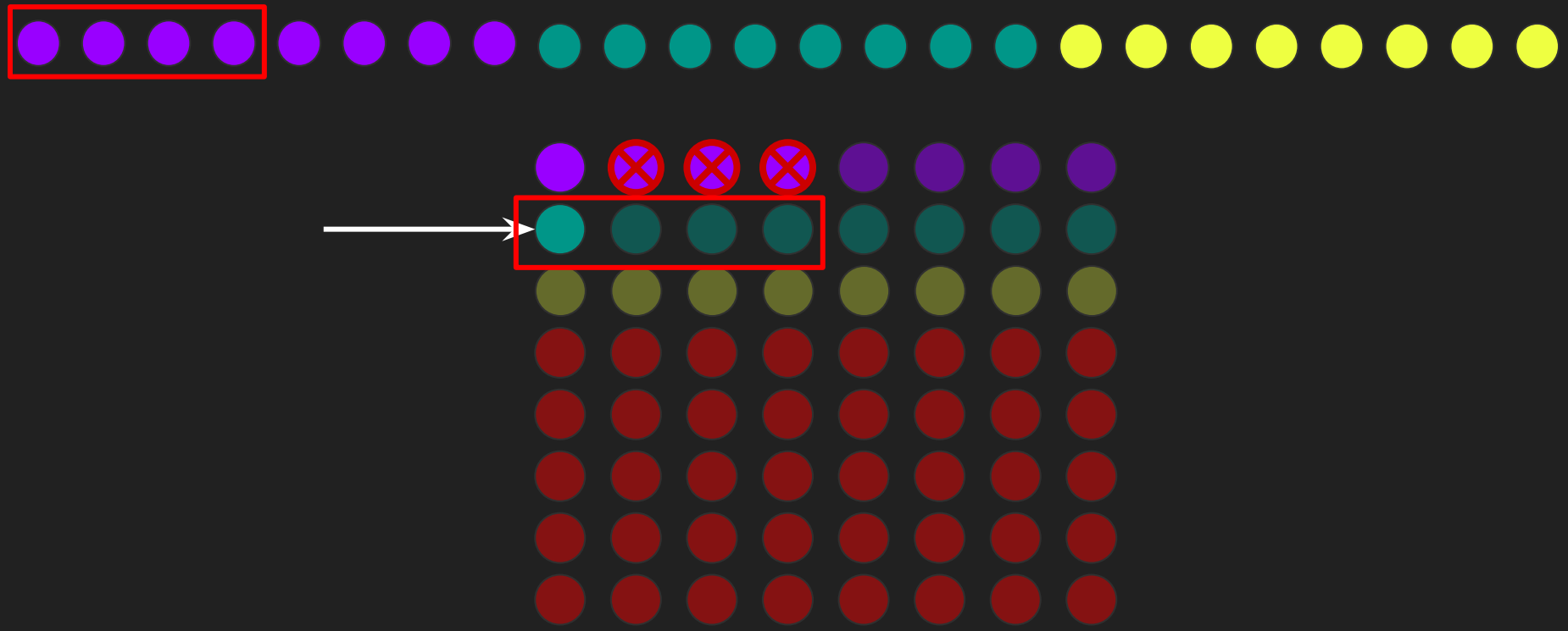


Outer-Loop Vectorization

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; ++i) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a = i;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = i, a1 = i+1, a2 = i+2, a3 = i+3;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;
  for (int j = 0; j < m; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;
  for (int j = 0; j < 2; ++j) {
    int v = A[j][i];
    a += v;
  }
  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j0 = 0;
  int v0 = A[j0][i];
  a += v0;

  int j1 = 1;
  int v1 = A[j1][i];
  a += v1;

  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j0 = 0;
  int v0 = A[j0][i];
  a += v0;

  int j1 = 1;
  int v1 = A[j1][i];
  a += v1;

  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j00 = 0, j01 = 0, j02 = 0, j03 = 0;
  int v0 = A[j0][i];
  a += v0;

  int j1 = 1;
  int v1 = A[j1][i];
  a += v1;

  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j00 = 0, j01 = 0, j02 = 0, j03 = 0;
  int v0 = A[j0][i];
  a += v0;

  int j1 = 1;
  int v1 = A[j1][i];
  a += v1;

  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j00 = 0, j01 = 0, j02 = 0, j03 = 0;
  int v00 = A[j00][i];   int v01 = A[j01][i+1];
  int v02 = A[j02][i+2]; int v03 = A[j03][i+3];
  a += v0;

  int j1 = 1;
  int v1 = A[j1][i];
  a += v1;

  B[i] = a;
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j00 = 0, j01 = 0, j02 = 0, j03 = 0;
  int v00 = A[j00][i];   int v01 = A[j01][i+1];
  int v02 = A[j02][i+2]; int v03 = A[j03][i+3];
  a += v0;

  int j1 = 1;
  int v1 = A[j1][i];
  a += v1;

  B[i] = a;
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j00 = 0, j01 = 0, j02 = 0, j03 = 0;
  int v00 = A[j00][i];   int v01 = A[j01][i+1];
  int v02 = A[j02][i+2]; int v03 = A[j03][i+3];
  a0 += v00; a1 += v01; a2 += v02; a3 += v03;

  int j1 = 1;
  int v1 = A[j1][i];
  a += v1;

  B[i] = a;
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j00 = 0, j01 = 0, j02 = 0, j03 = 0;
  int v00 = A[j00][i];   int v01 = A[j01][i+1];
  int v02 = A[j02][i+2]; int v03 = A[j03][i+3];
  a0 += v00; a1 += v01; a2 += v02; a3 += v03;

  int j10 = 1, j11 = 1, j12 = 1, j13 = 1;
  int v10 = A[j10][i];   int v11 = A[j11][i+1];
  int v12 = A[j12][i+2]; int v13 = A[j13][i+3];
  a0 += v10; a1 += v11; a2 += v12; a3 += v13;

  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j00 = 0, j01 = 0, j02 = 0, j03 = 0;
  int v00 = A[j00][i];   int v01 = A[j01][i+1];
  int v02 = A[j02][i+2]; int v03 = A[j03][i+3];
  a0 += v00; a1 += v01; a2 += v02; a3 += v03;

  int j10 = 1, j11 = 1, j12 = 1, j13 = 1;
  int v10 = A[j10][i];   int v11 = A[j11][i+1];
  int v12 = A[j12][i+2]; int v13 = A[j13][i+3];
  a0 += v10; a1 += v11; a2 += v12; a3 += v13;

  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j0 = 0;
  int v00 = A[j0][i];   int v01 = A[j0][i+1];
  int v02 = A[j0][i+2]; int v03 = A[j0][i+3];
  a0 += v00; a1 += v01; a2 += v02; a3 += v03;

  int j10 = 1, j11 = 1, j12 = 1, j13 = 1;
  int v10 = A[j10][i];   int v11 = A[j11][i+1];
  int v12 = A[j12][i+2]; int v13 = A[j13][i+3];
  a0 += v10; a1 += v11; a2 += v12; a3 += v13;

  B[i] = a;
}
```

Outer-Loop Hand-Vectorized

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;

  int j0 = 0;
  int v00 = A[j0][i];   int v01 = A[j0][i+1];
  int v02 = A[j0][i+2]; int v03 = A[j0][i+3];
  a0 += v00; a1 += v01; a2 += v02; a3 += v03;

  int j1 = 1;
  int v10 = A[j1][i];   int v11 = A[j1][i+1];
  int v12 = A[j1][i+2]; int v13 = A[j1][i+3];
  a0 += v10; a1 += v11; a2 += v12; a3 += v13;

  B[i] = a;
}
```

Sum Columns Original

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;
  for (int j = 0; j < m; ++j) {
    int v0 = A[j][i];   int v1 = A[j][i+1];
    int v2 = A[j][i+2]; int v3 = A[j][i+3];

    a0 += v0; a1 += v1; a2 += v2; a3 += v3;
  }
  B[i] = a;
}
```

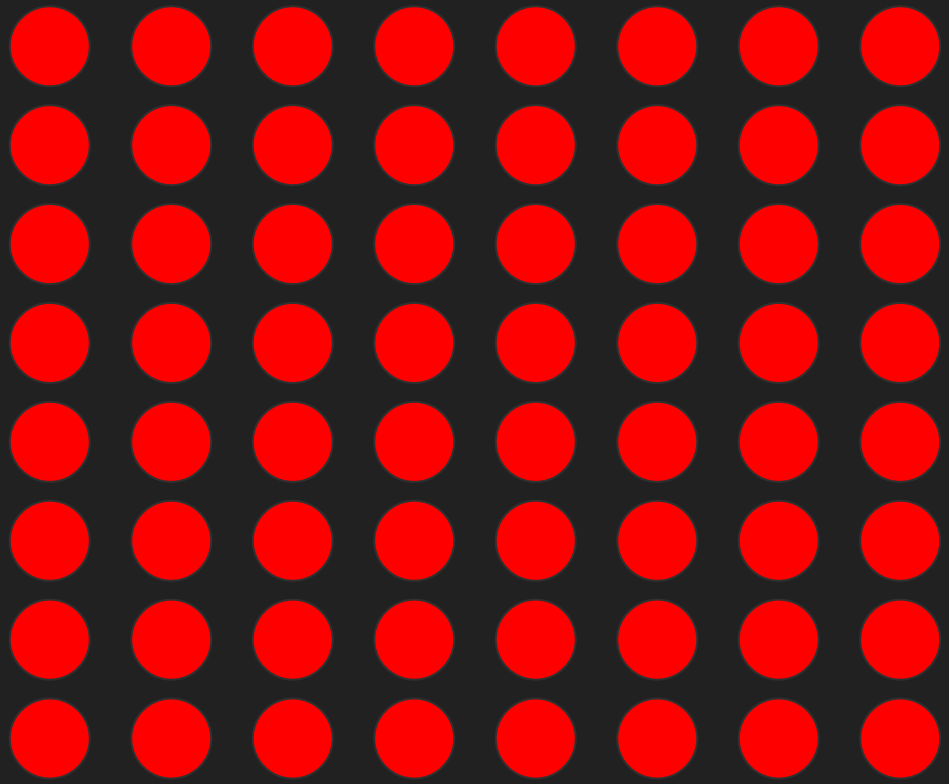
Sum Columns Original

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;
  for (int j = 0; j < m; ++j) {
    int v0 = A[j][i];   int v1 = A[j][i+1];
    int v2 = A[j][i+2]; int v3 = A[j][i+3];

    a0 += v0; a1 += v1; a2 += v2; a3 += v3;
  }
  B[i] = a;
}
```

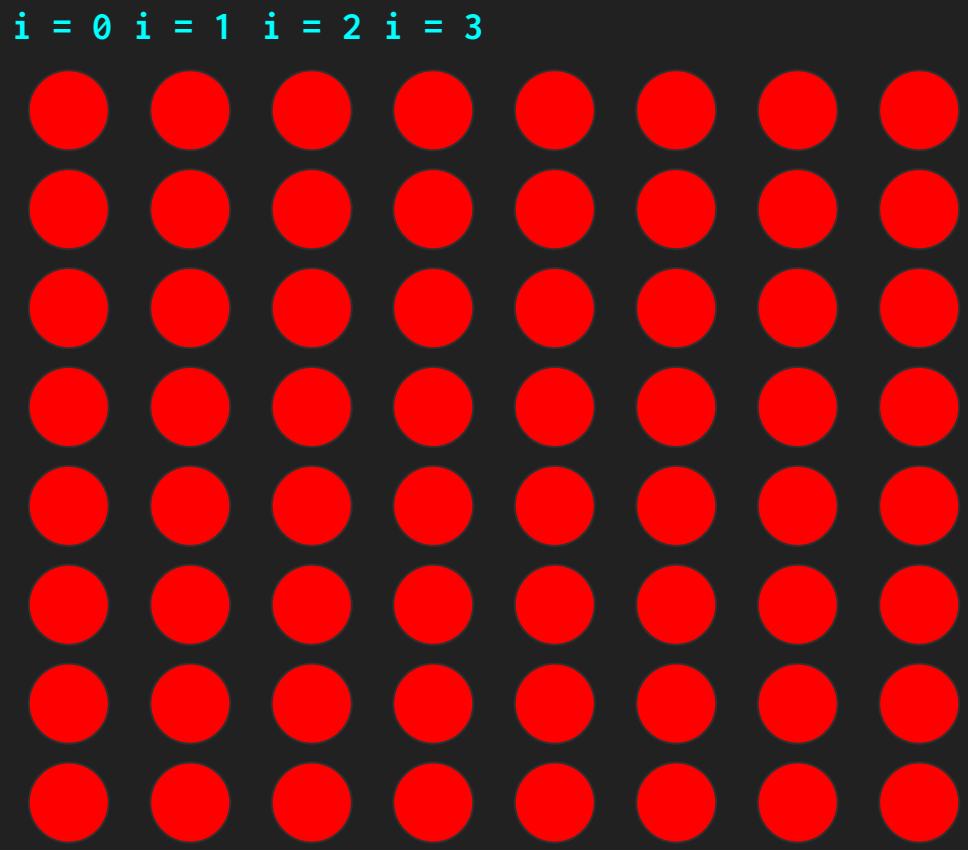
Sum Columns Original

```
for (int i = 0; i < n; i += 4) {
  int a0 = 0, a1 = 0, a2 = 0, a3 = 0;
  for (int j = 0; j < m; ++j) {
    int v0 = A[j][i];   int v1 = A[j][i+1];
    int v2 = A[j][i+2]; int v3 = A[j][i+3];

    a0 += v0; a1 += v1; a2 += v2; a3 += v3;
  }
  B[i] = a0;   B[i+1] = a1;
  B[i+2] = a2; B[i+3] = a3;
}
```

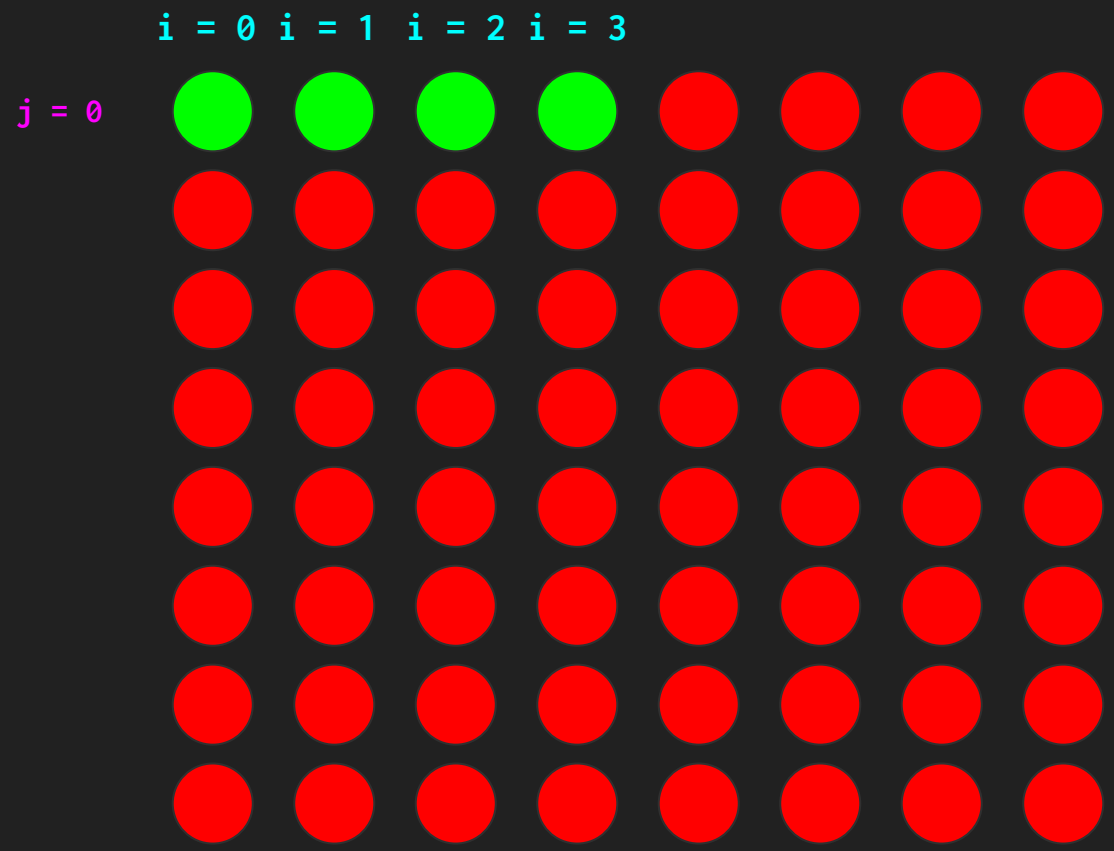
Memory Space



Memory Space



Memory Space



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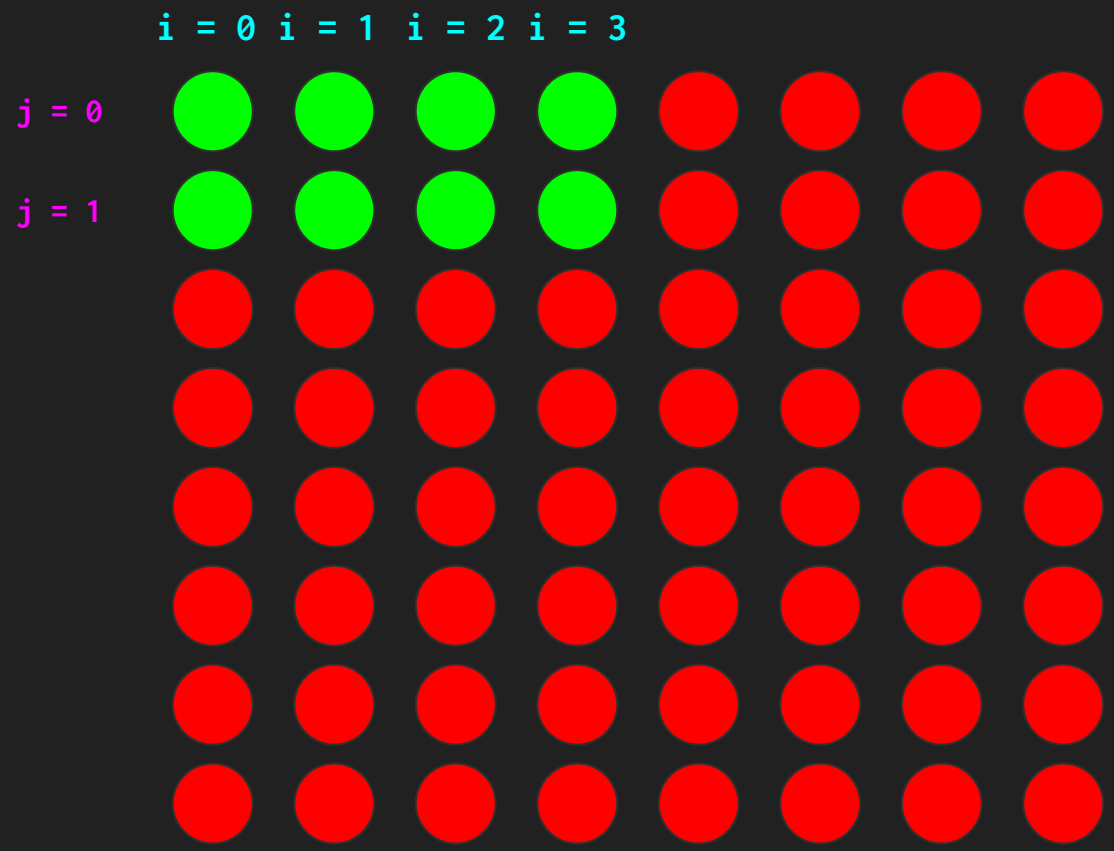

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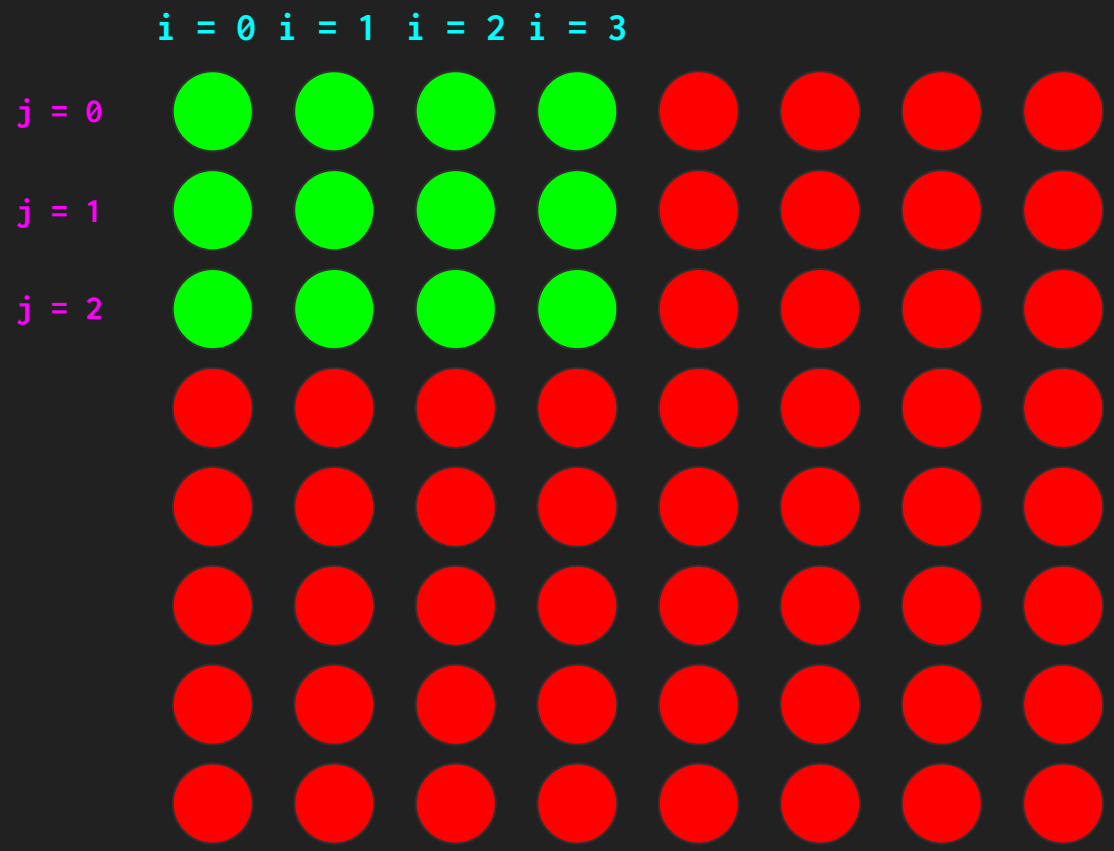
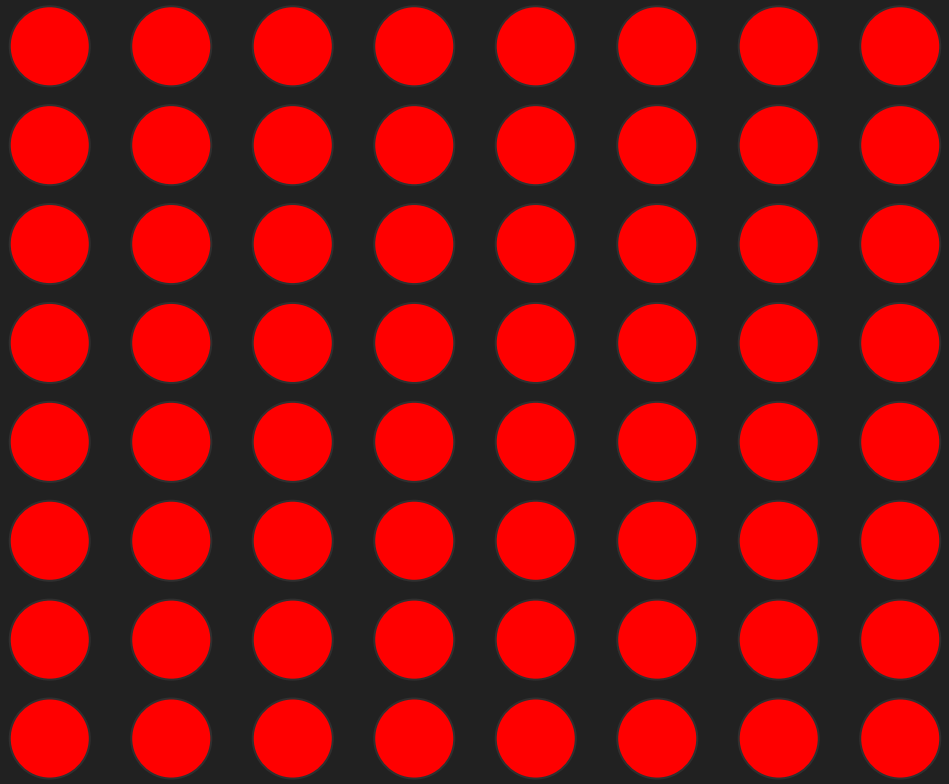
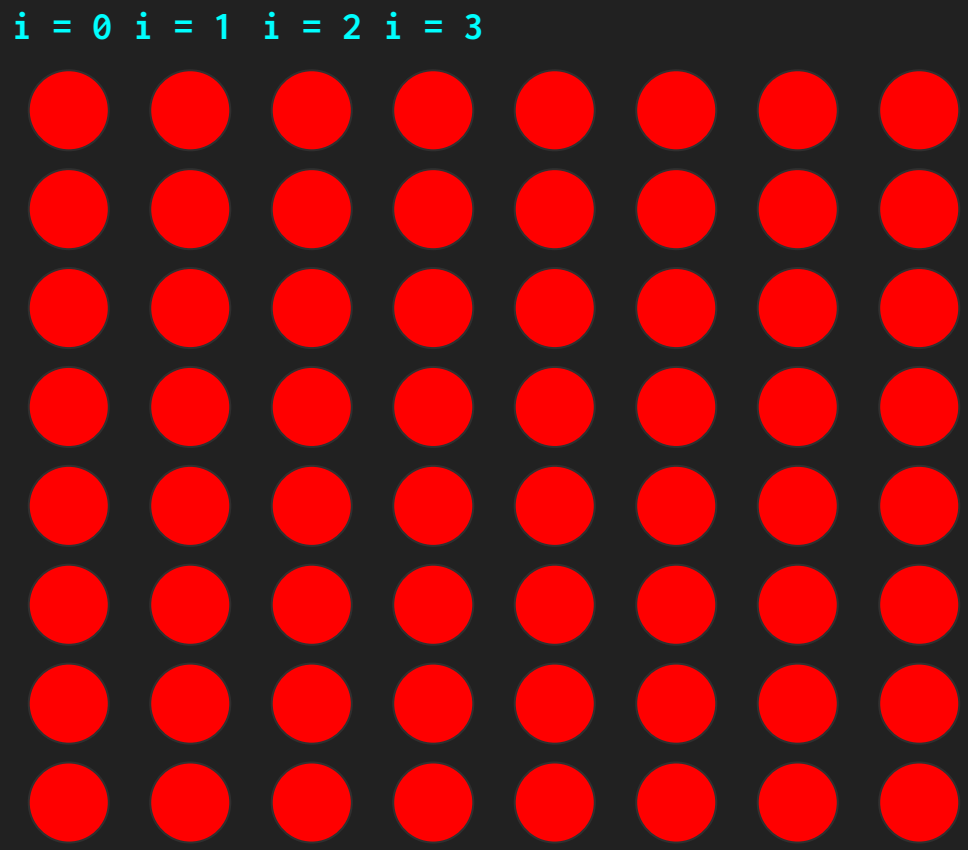


Outer-Loop Parallelization (i.e., Multi-threading)

Memory Space



Memory Space



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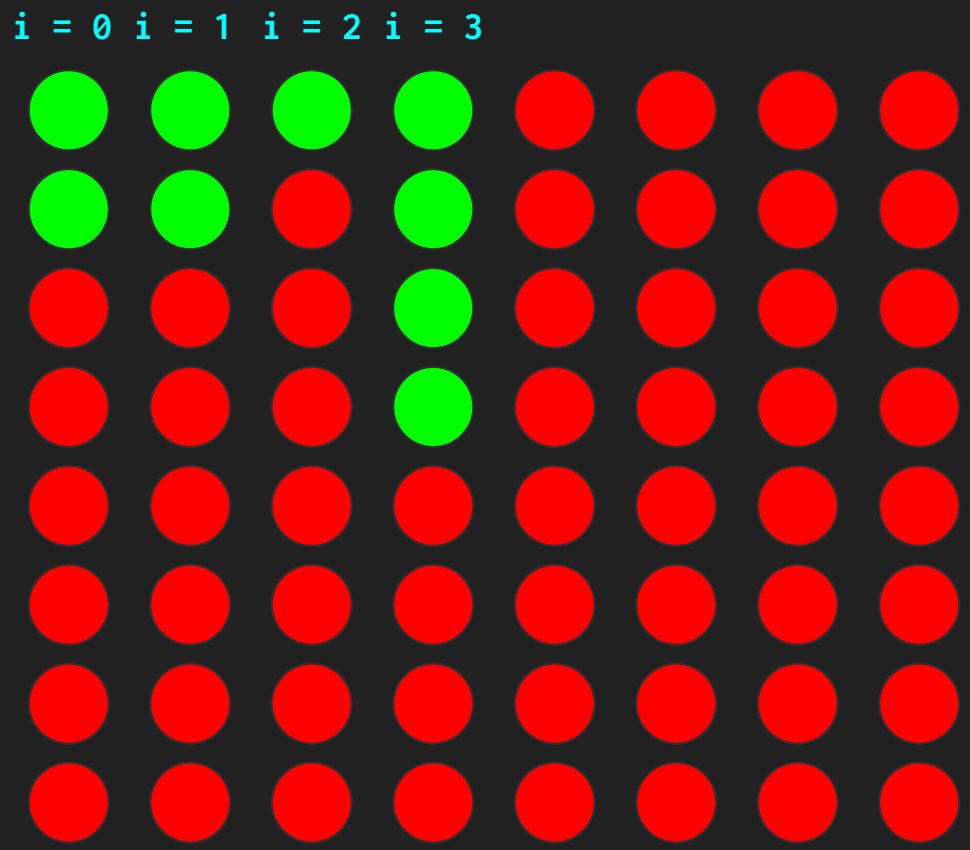
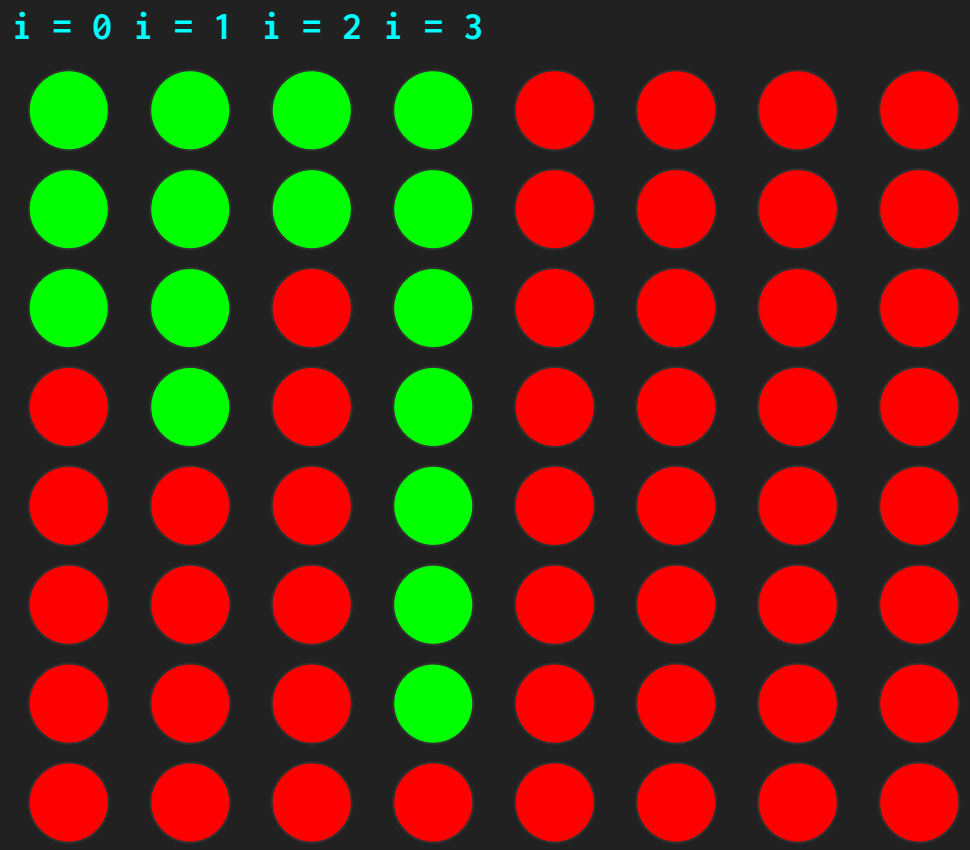


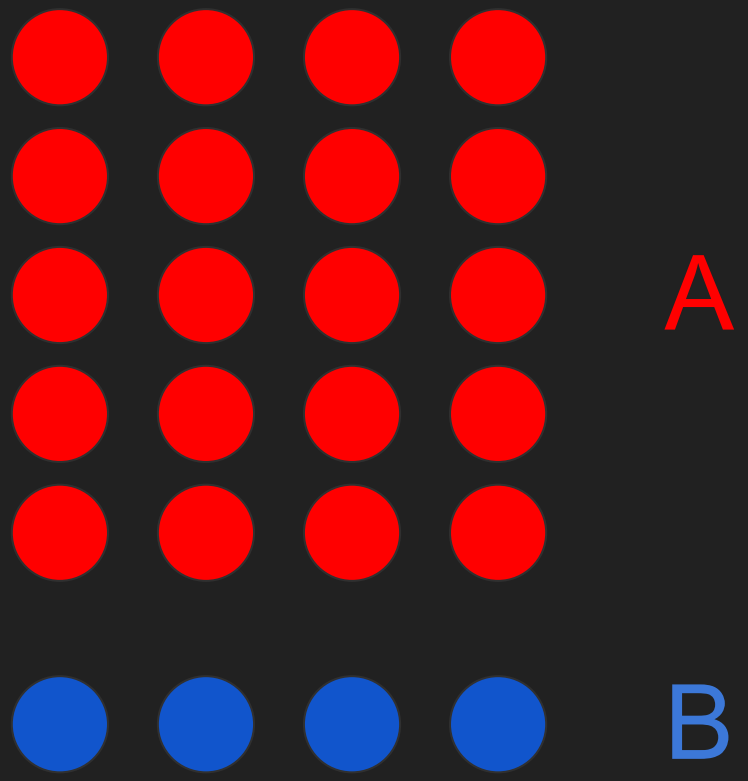
Memory Space



Sum Columns Conditionally

```
for (int i = 0; i < n; ++i) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    bool p = C[j];
    if (p) {
      int v = A[j][i];
      a += v;
    }
  }
  B[i] = a;
}
```

Memory Space



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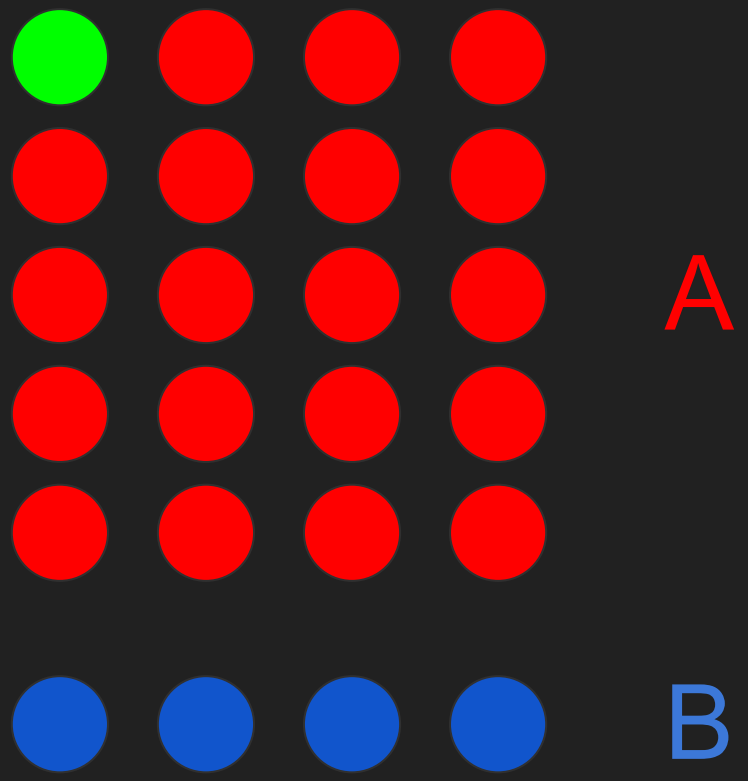

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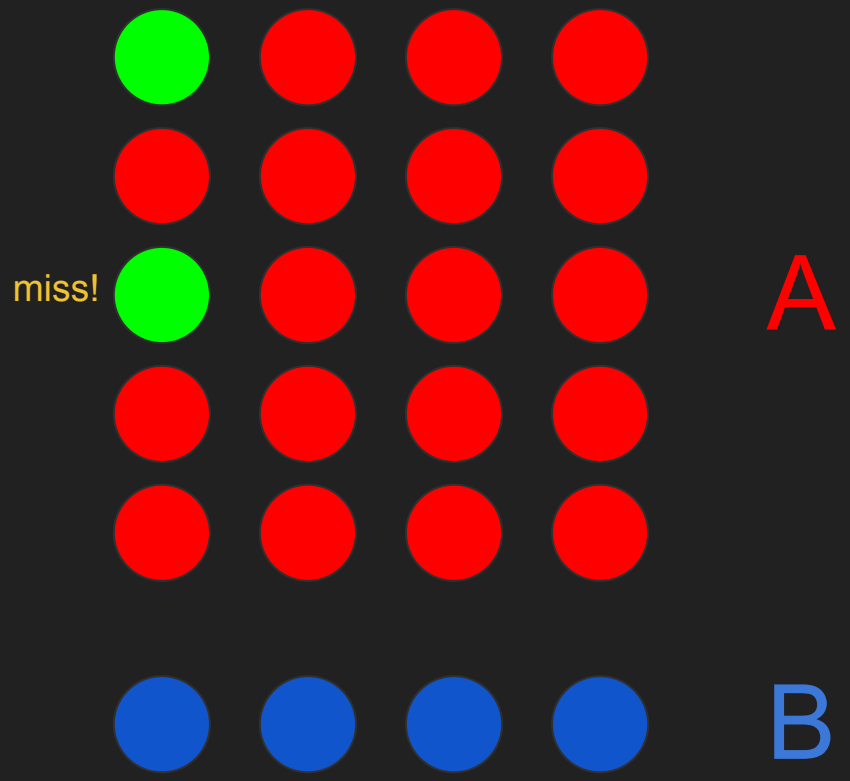

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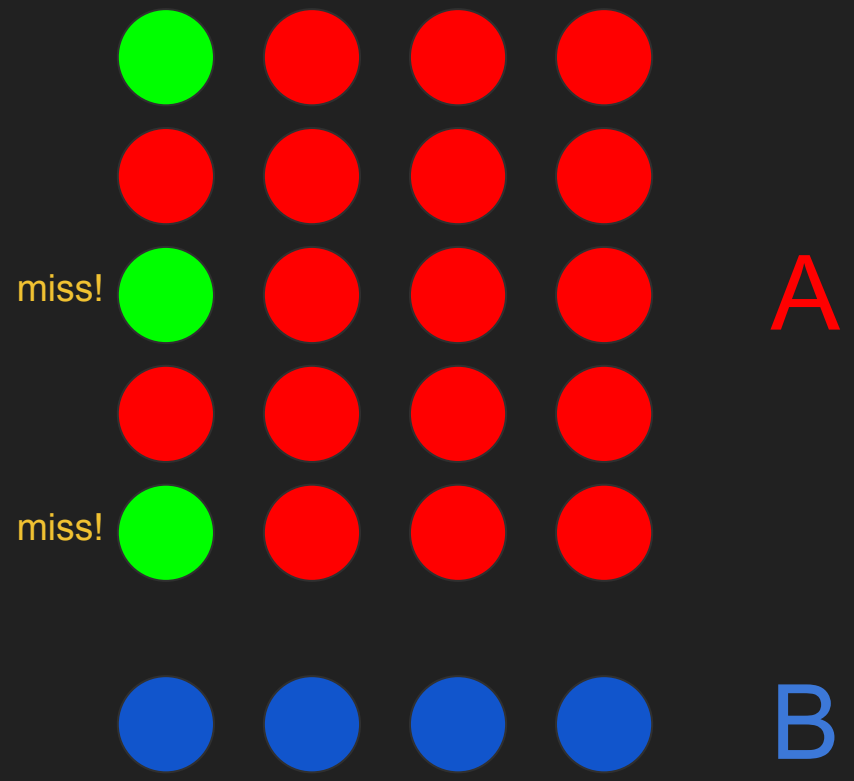

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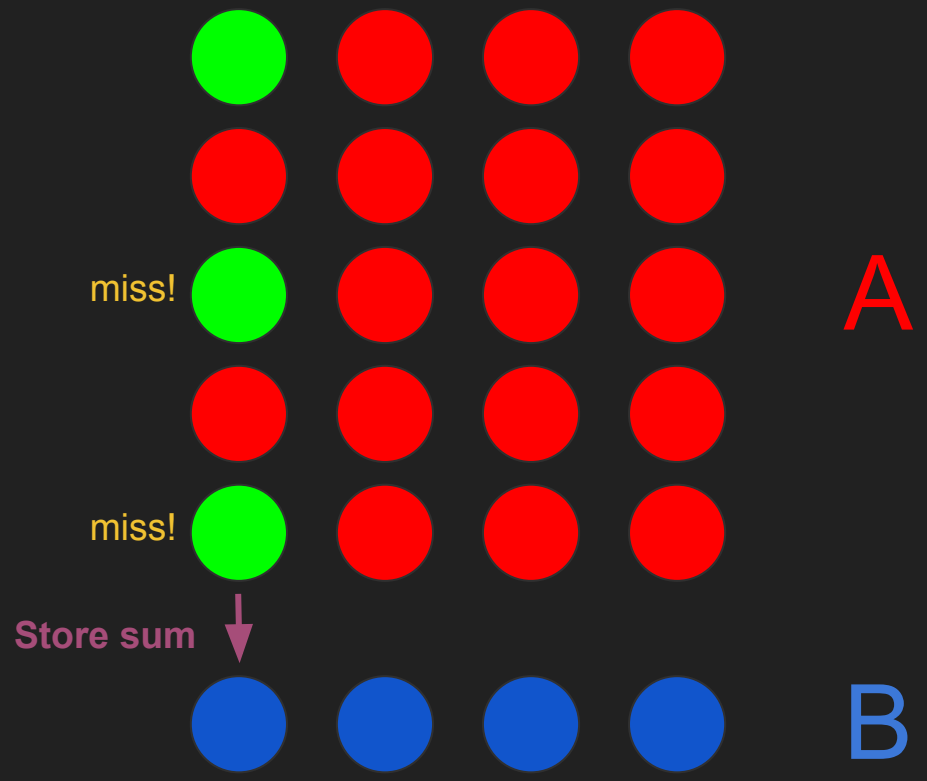


Uniformity

A uniform value is characterized in relation to a loop and is one that does <u>not</u> vary *because of this loop*.

Divergence

```
Divergent = !Uniform
```

Uniformity in Innermost Loops

```
for (int i = 0; i < N; ++i) {
  int v = 1 + 2;
  a[i] = v;
}
```

Uniformity in Innermost Loops

```
for (int i = 0; i < N; ++i) {
  int v = 1 + 2;
  a[i] = v;
}
```

v is uniform and also loop-invariant

Hoist Out

```
int v = 1 + 2;
for (int i = 0; i < N; ++i) {
  a[i] = v;
}
```

Conditional Code

```
for (int i = 0; i < n; ++i) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    bool p = C[j];
    if (p) {
      int v = A[j][i];
      a += v;
    }
  }
  B[i] = a;
}
```

Conditional Code

```
for (int i = 0; i < n; ++i) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    bool p = C[j];
    if (p) {
      int v = A[j][i];
      a += v;
    }
  }
  B[i] = a;
}
```

What is p in the i-loop?

Conditional Code

```
for (int i = 0; i < n; ++i) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    bool p = C[j];
    if (p) {
      int v = A[j][i];
      a += v;
    }
  }
  B[i] = a;
}
```

What is p in the i-loop?

Uniform? ✓

Conditional Code

```
for (int i = 0; i < n; ++i) {
  int a = 0;
  for (int j = 0; j < m; ++j) {
    bool p = C[j];
    if (p) {
      int v = A[j][i];
      a += v;
    }
  }
  B[i] = a;
}
```

What is p in the i-loop?

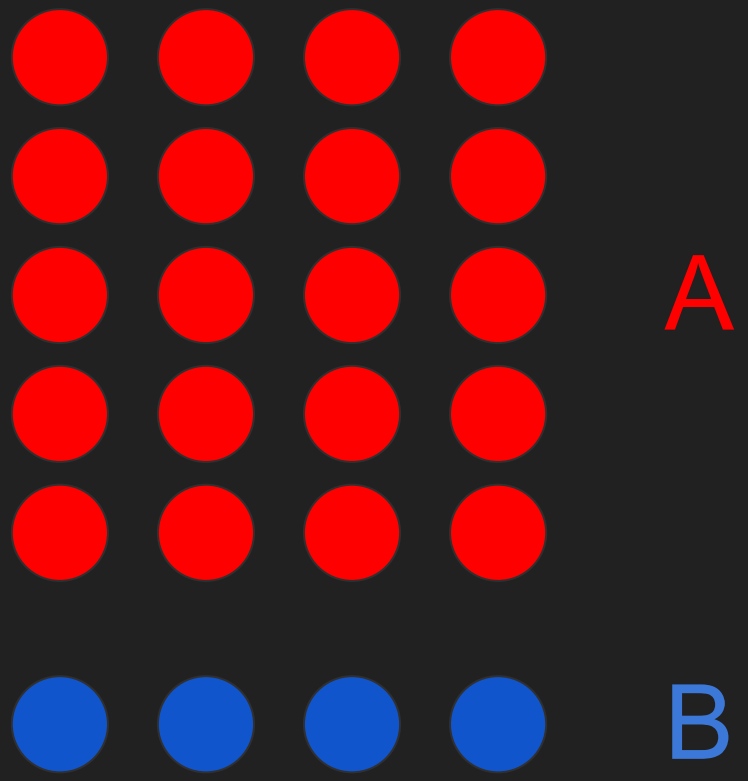
Uniform? ✓

Loop-Invariant? ✗

Uniformity Enables Outer-Loop Vectorization

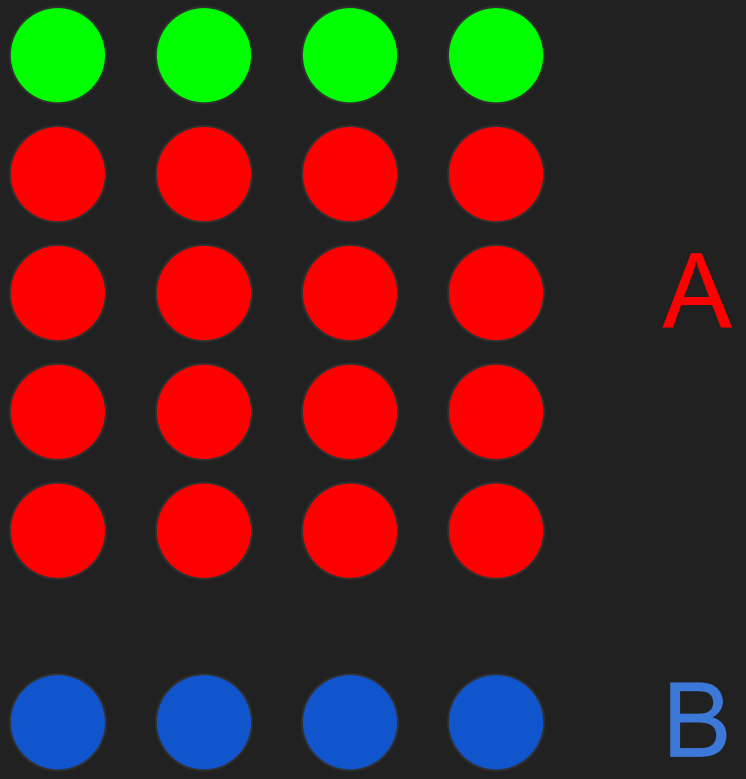
```
for (int i = 0; i < end; i += 4) {  // vectorized
  __m128i a = [0,0,0,0];
  for (int j = 0; j < m; ++j) {
    bool p = C[j];
    if (p) {
      __m128i v = loadu4(&A[j][i];);
      a = add4(a, v);
    }
  }
  storeu4(&B[i], a);
}
… residual
```

Memory Space



Memory Space

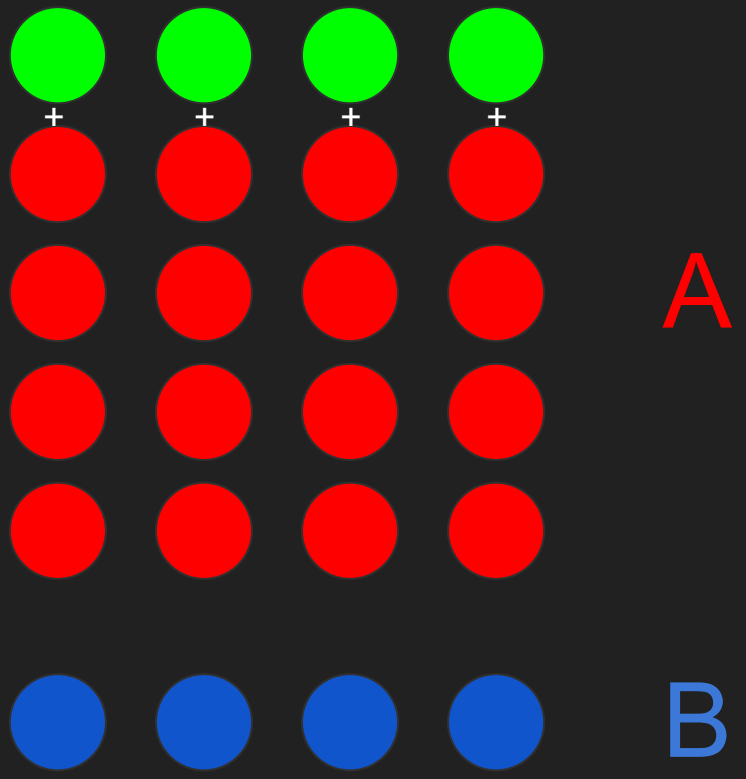
```
p = true
```



Memory Space

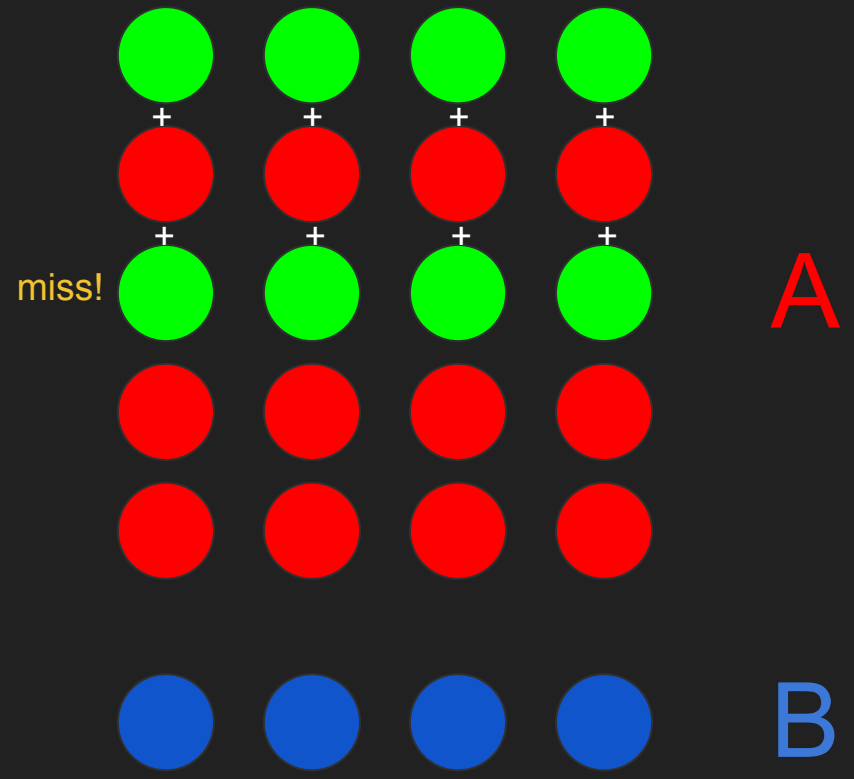
```
p = true

p = false
```



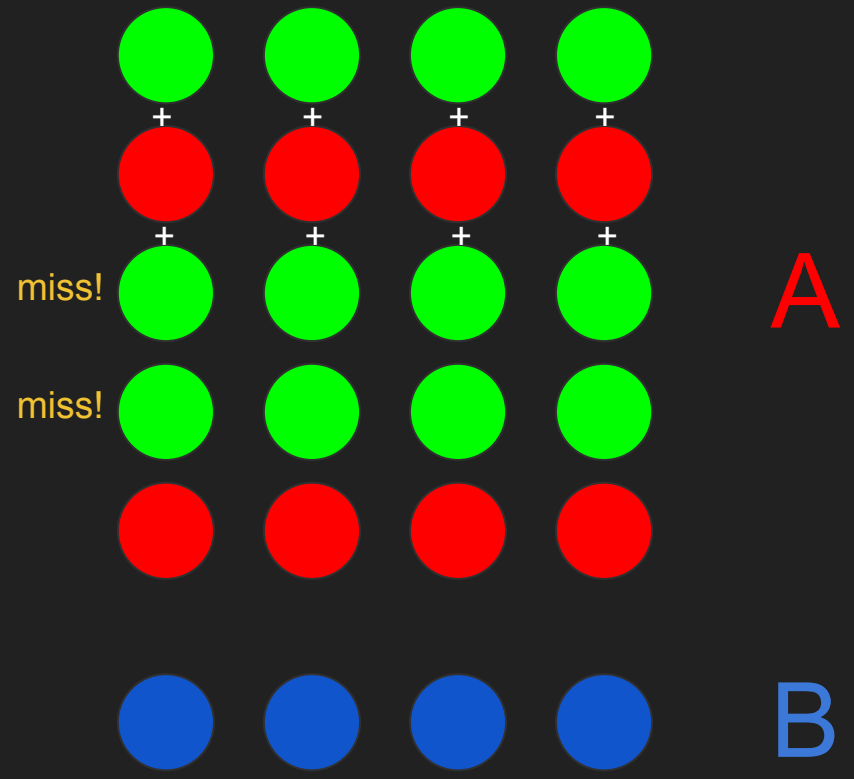
Memory Space

```
p = true
p = false
p = true
```



Memory Space

```
p = true
p = false
p = true
p = true
```



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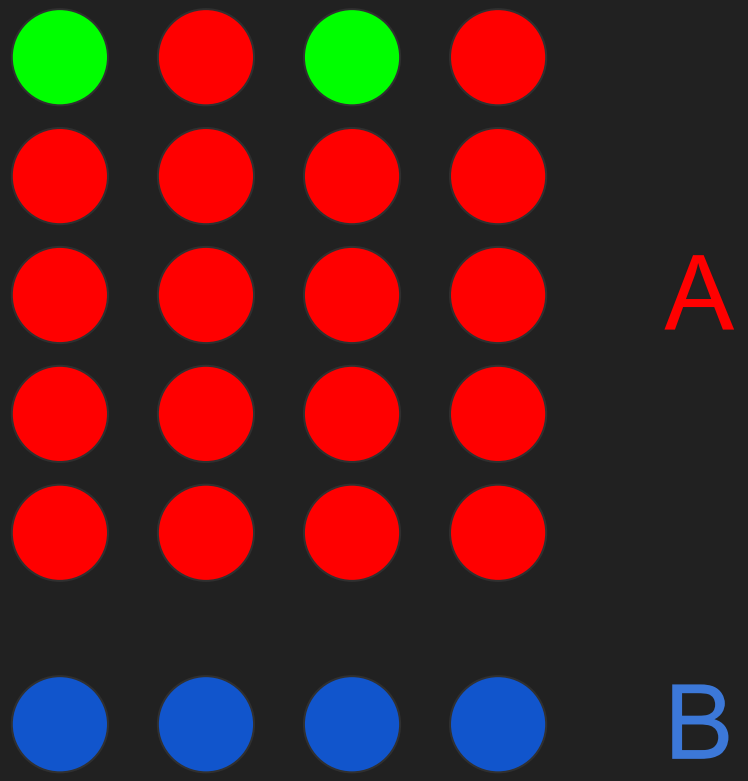

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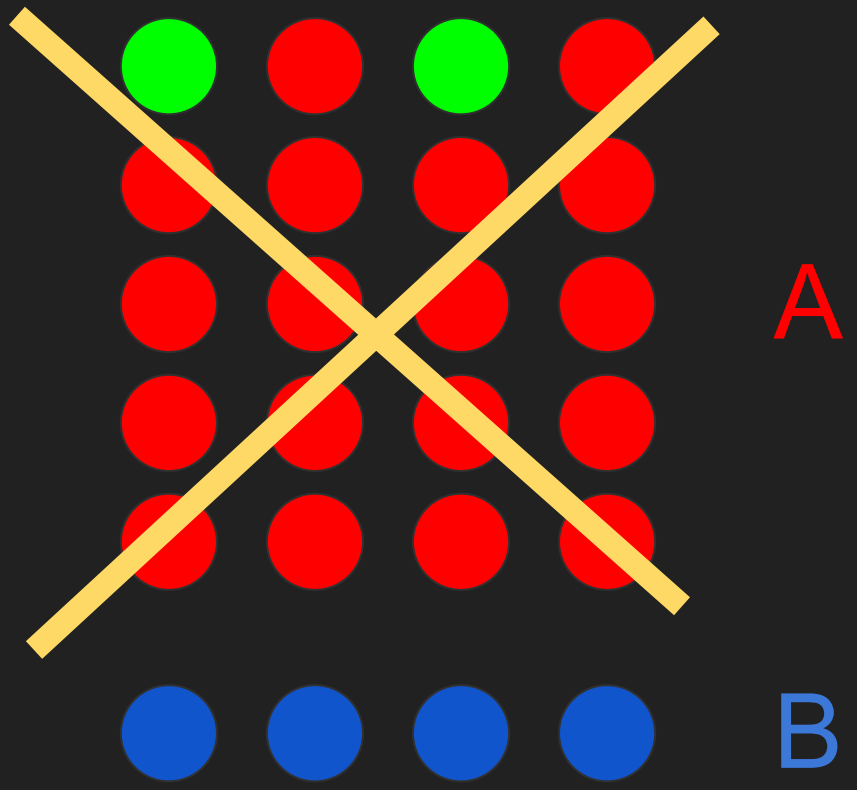


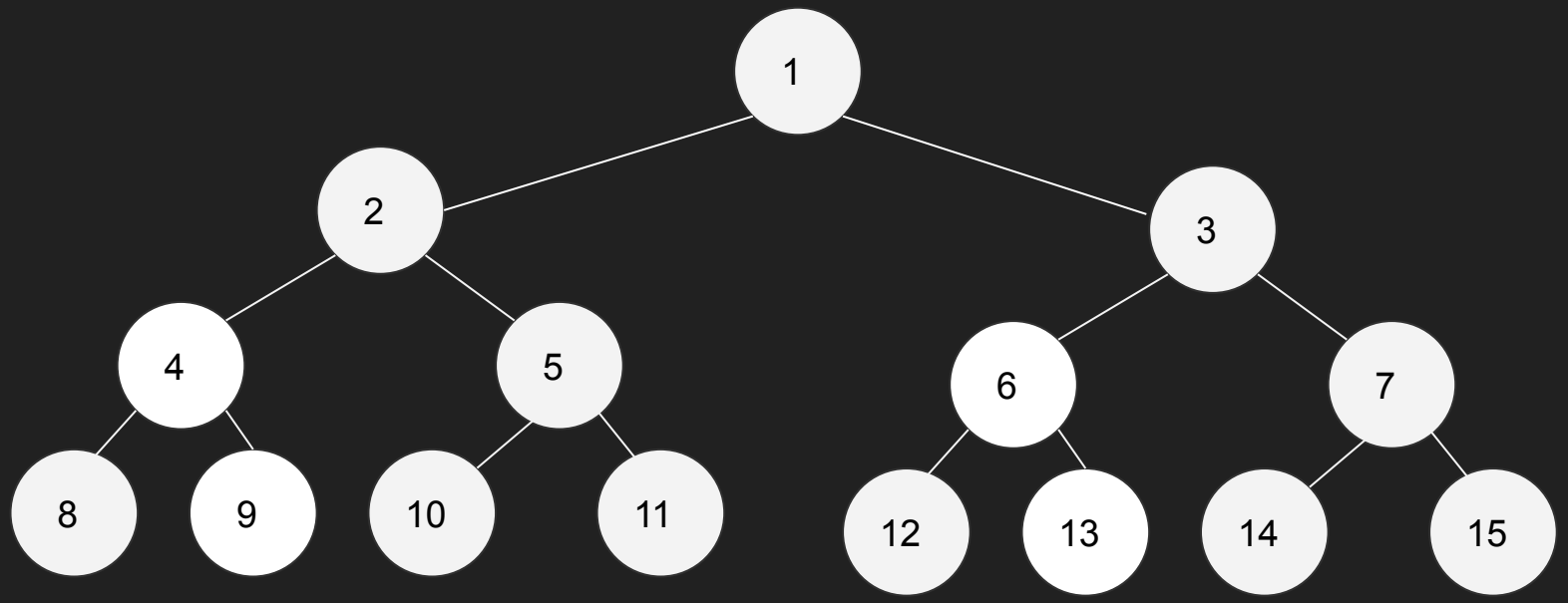
Region Vectorizer (RV)

RV provides a unified interface to vectorize code regions, such as inner and outer loops, up to whole functions.

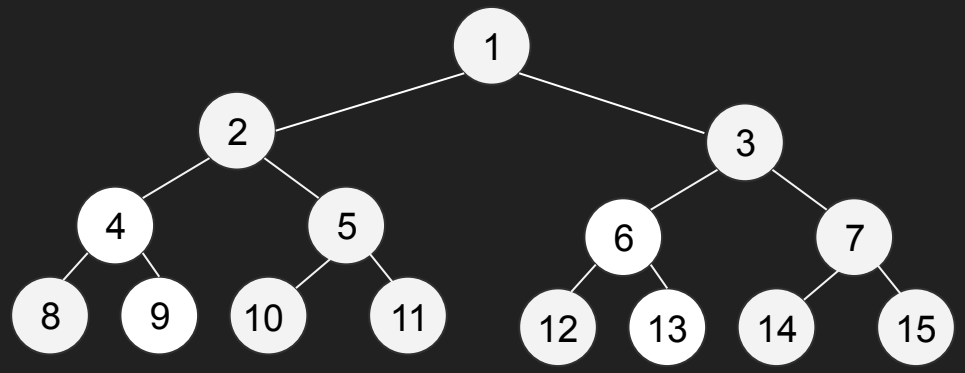
https://github.com/cdl-saarland/rv

Recursive Tree Traversal Vectorization

Tree



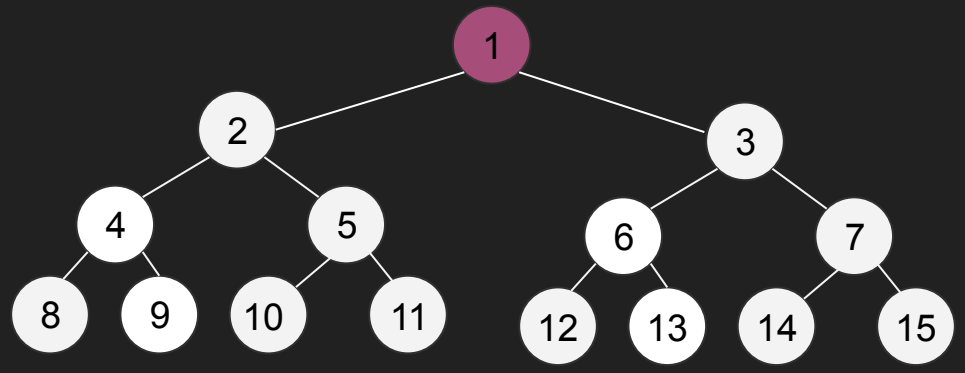
Tree



Nodes

	1	2	4	8	9	5	10	11	3	6	12	13	7	14	15
Traversals															
A															
B															
C															
D															

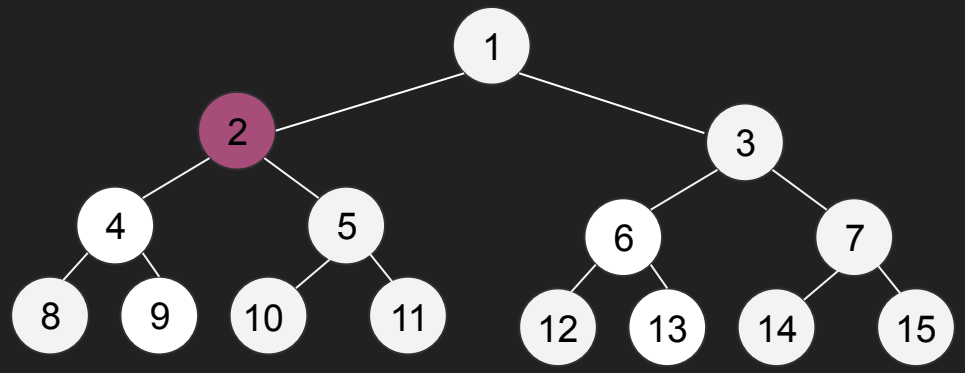
Tree



Nodes

	1	2	4	8	9	5	10	11	3	6	12	13	7	14	15
Traversals															
A															
B															
C															
D															

Tree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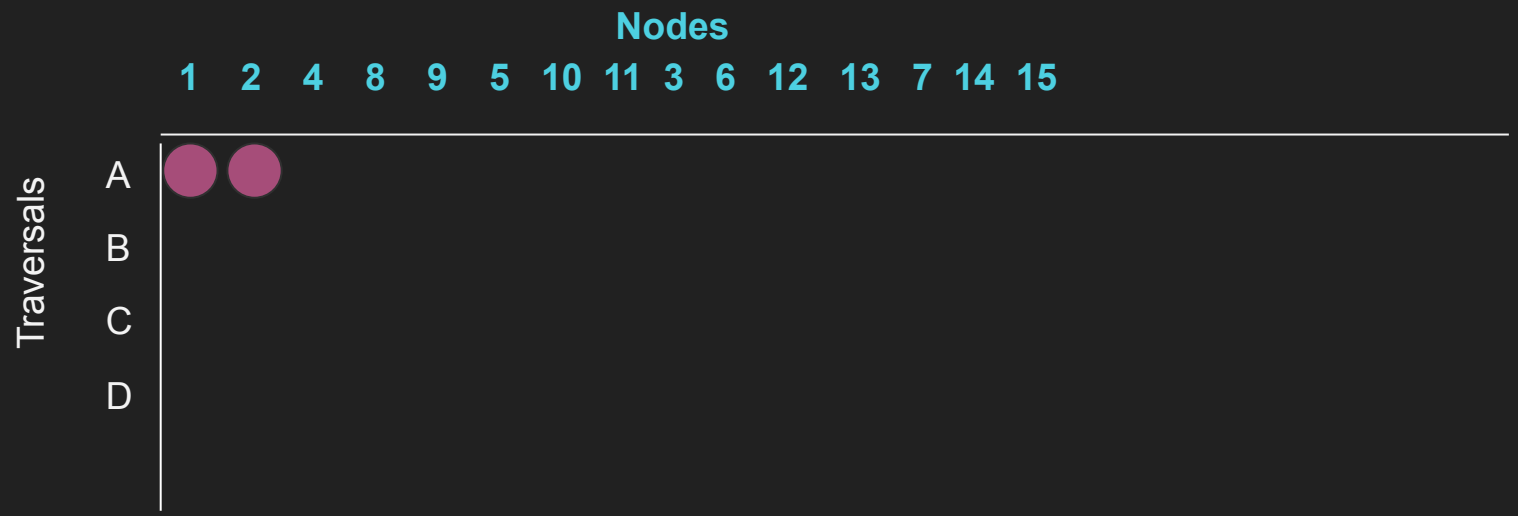
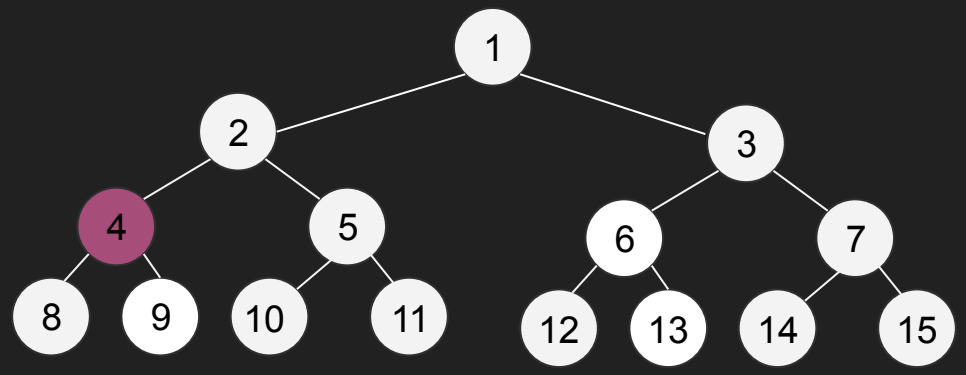

Nodes
1 2 4 8 9 5 10 11 3 6 12 13 7 14 15
Traversals
A
B
C
D

Tree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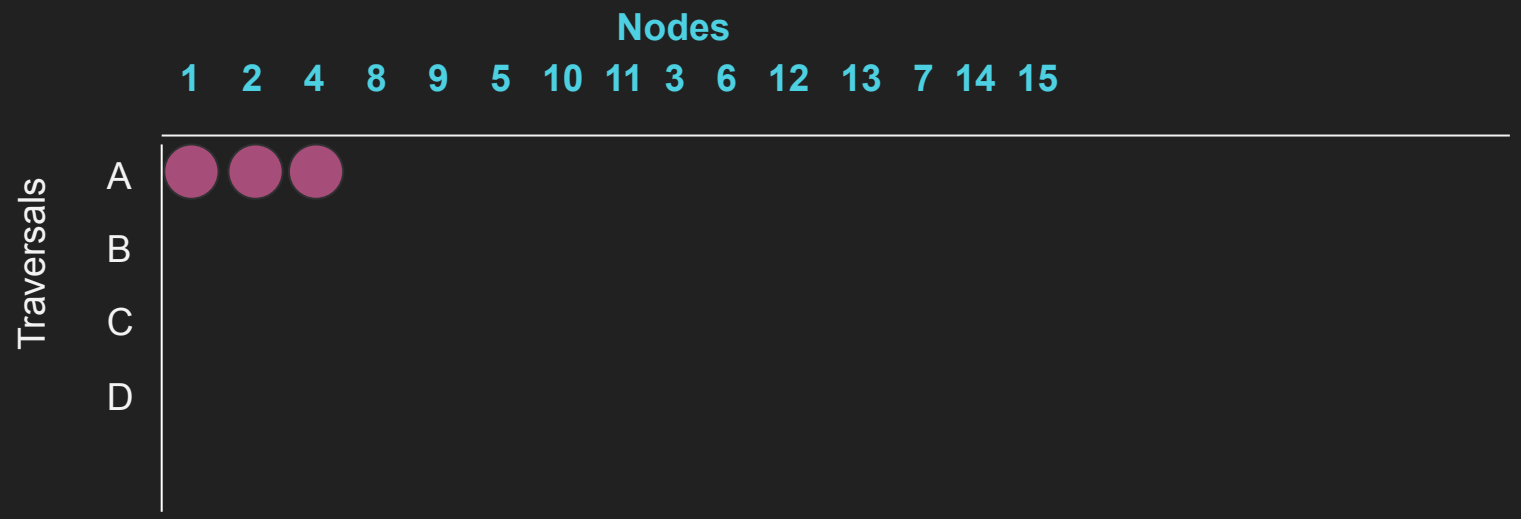
Nodes
1 2 4 8 9 5 10 11 3 6 12 13 7 14 15
Traversals
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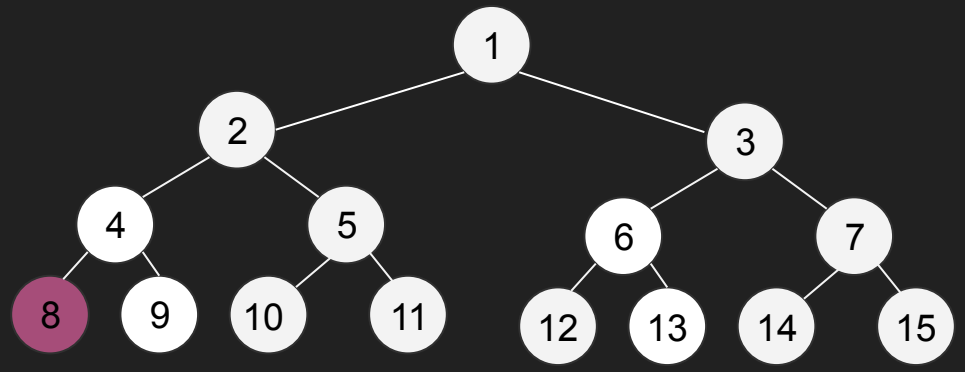
Tree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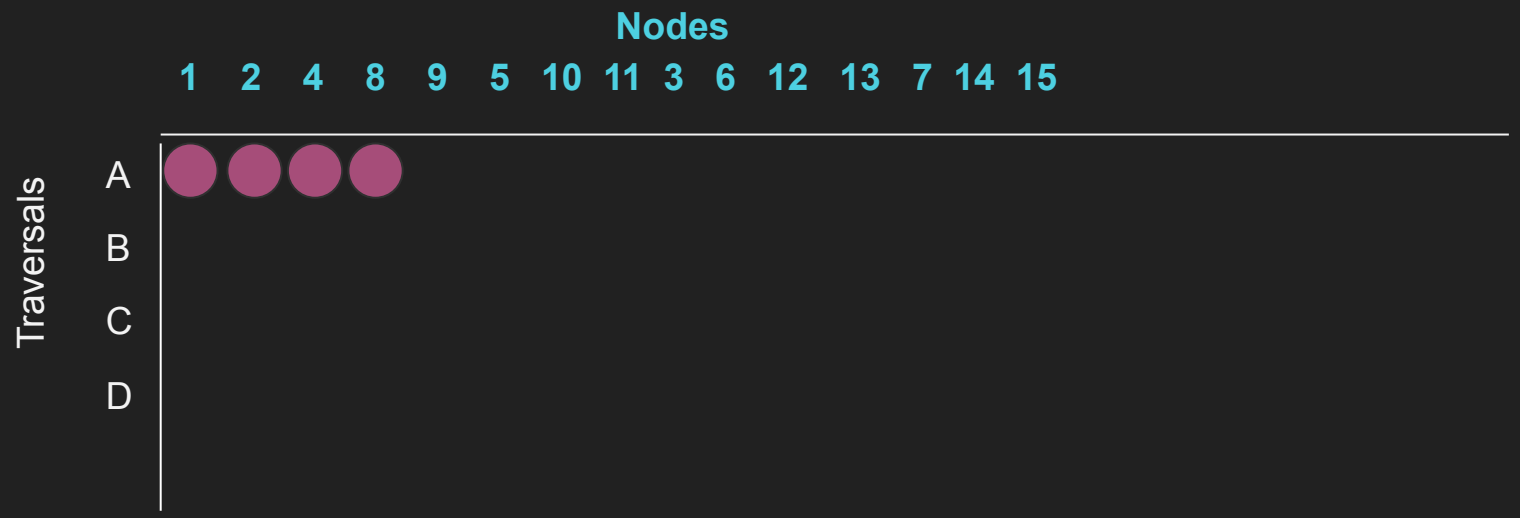
Nodes
1 2 4 8 9 5 10 11 3 6 12 13 7 14 15
Traversals
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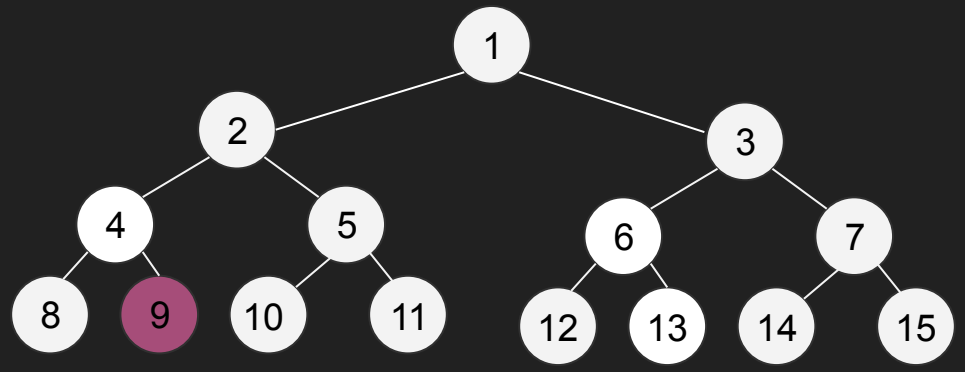
Tree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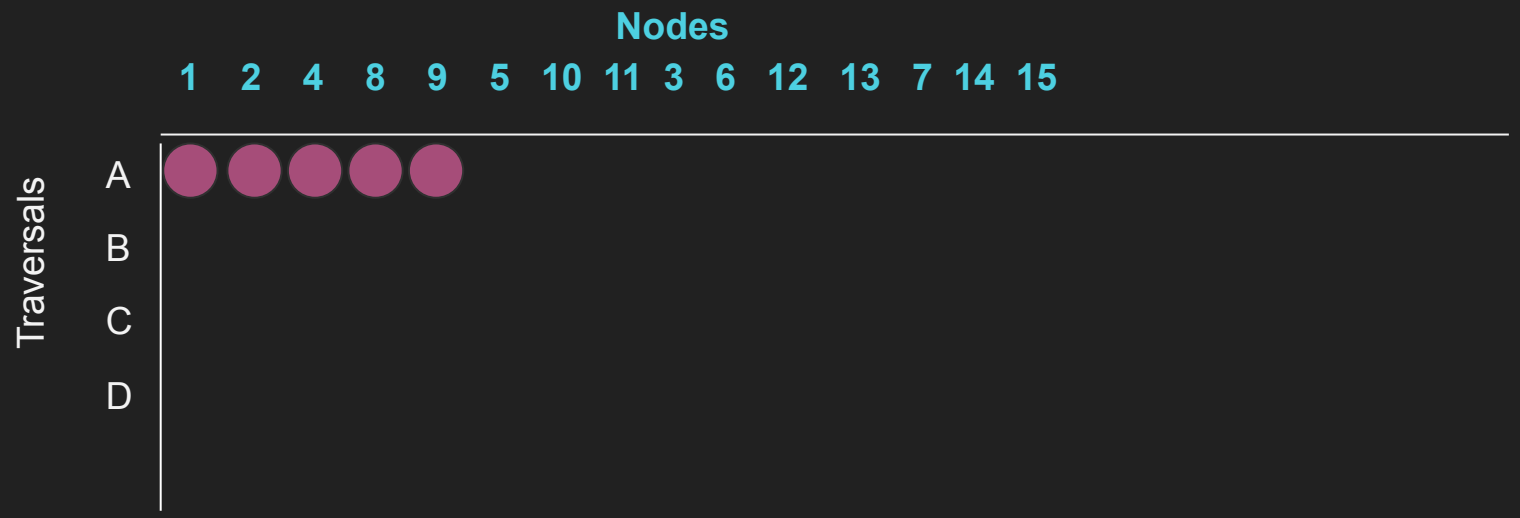
Nodes
1 2 4 8 9 5 10 11 3 6 12 13 7 14 15
Traversals
A
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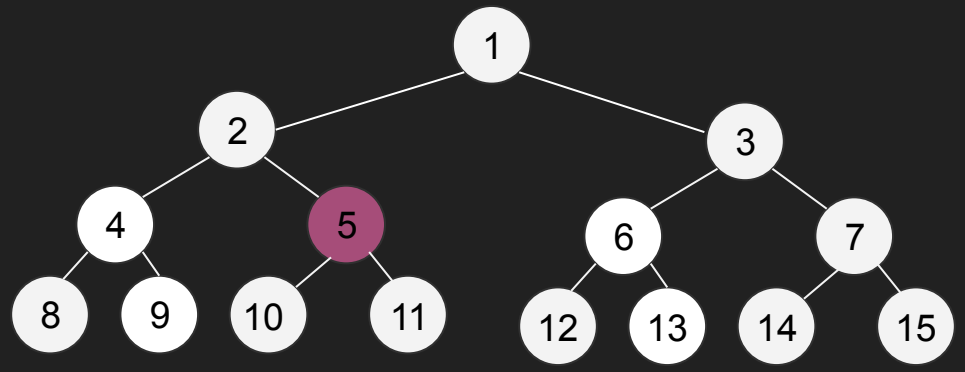
Tree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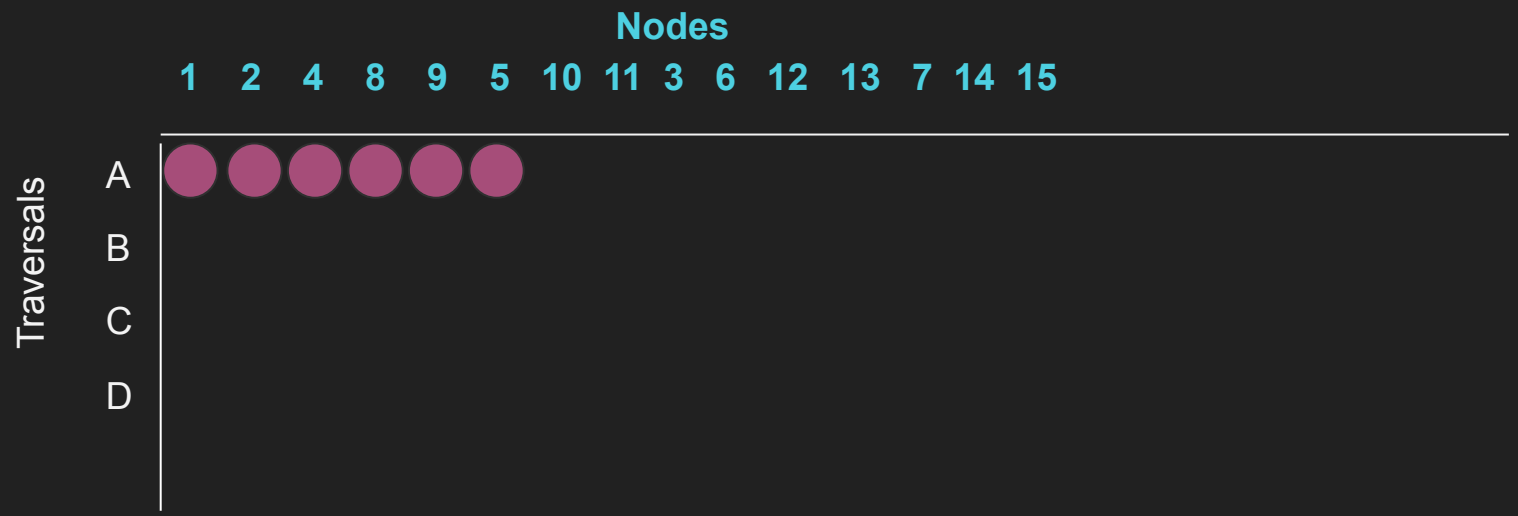
Nodes
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Traversals
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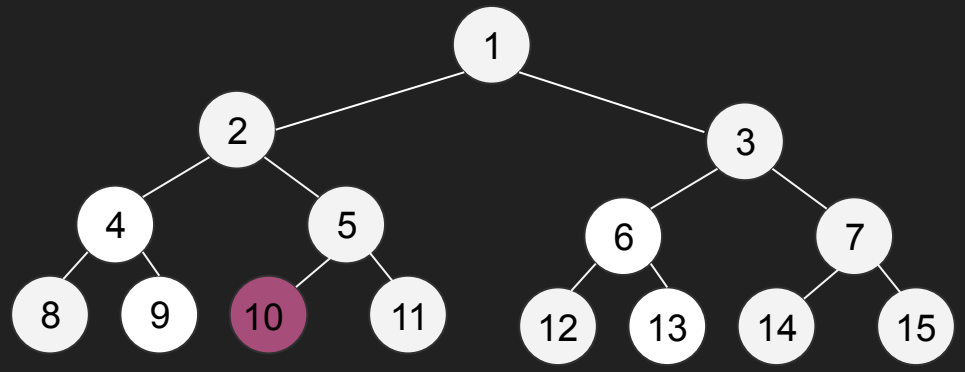
Tree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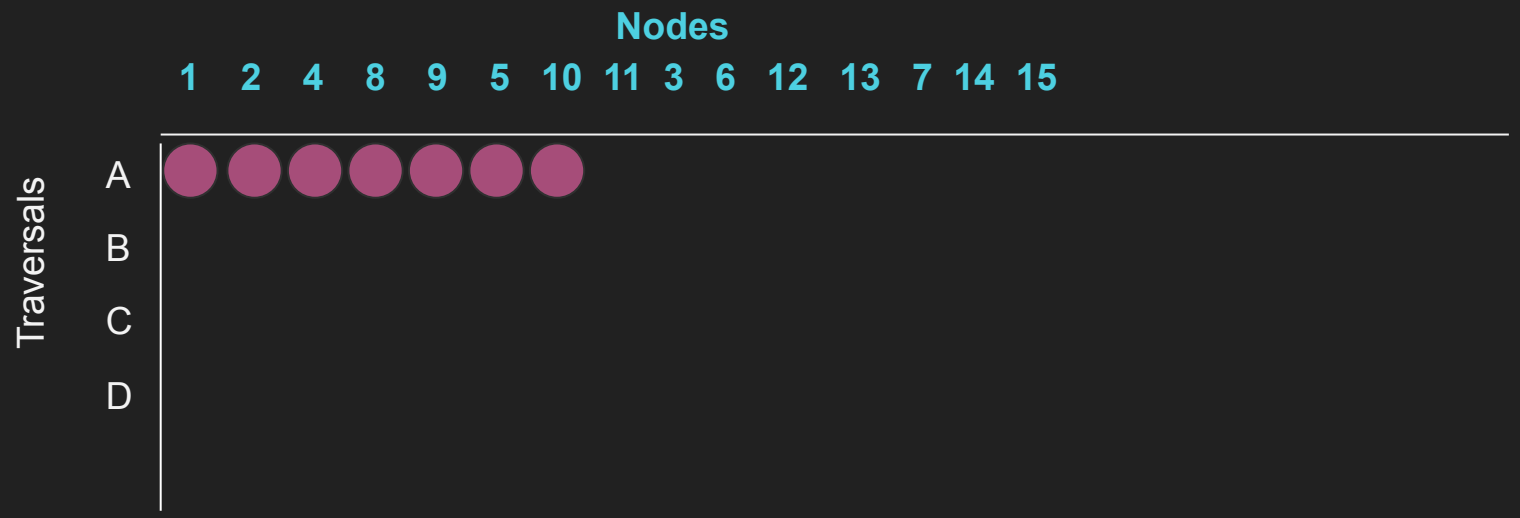
Nodes
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Traversals
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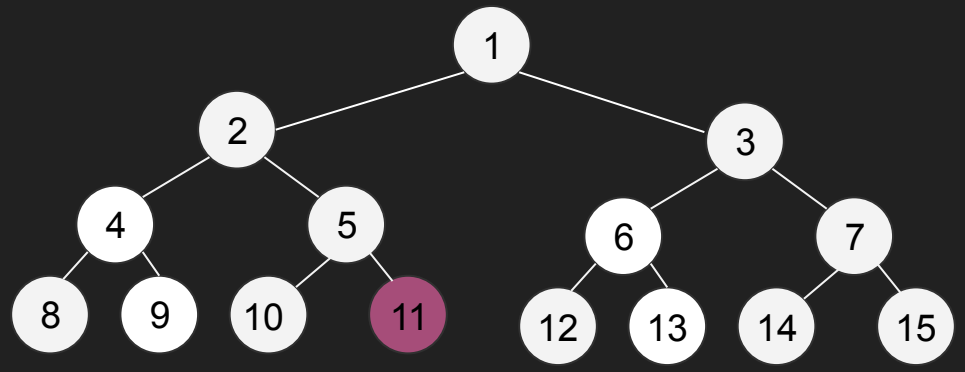
Tree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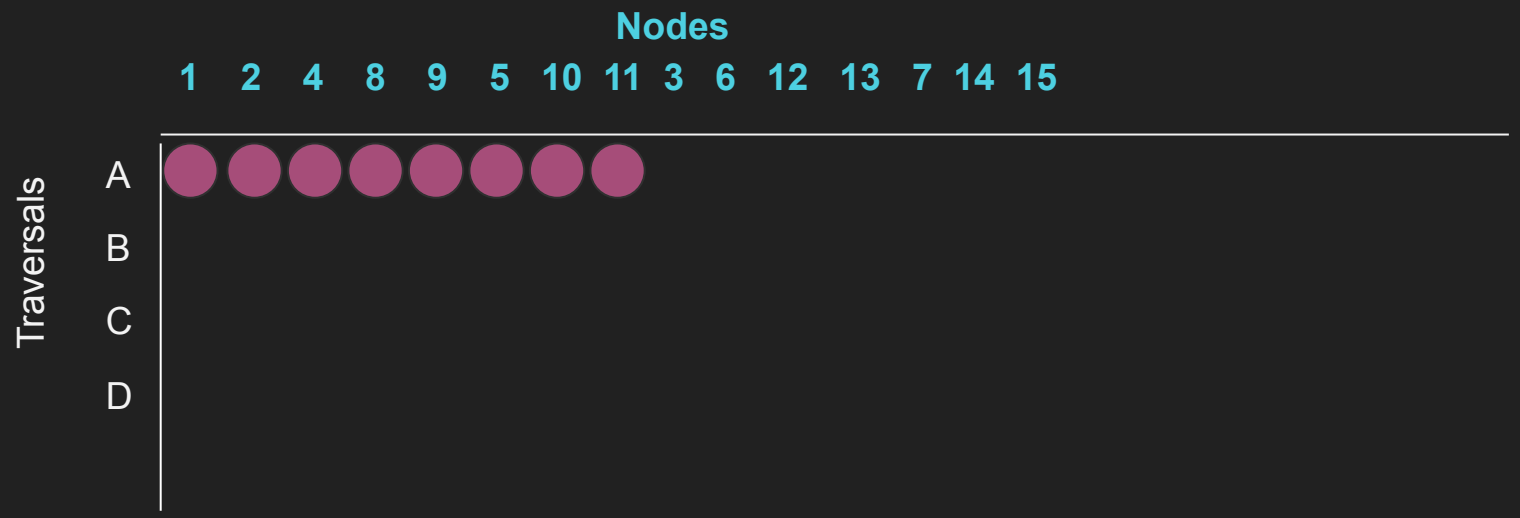
Nodes
1 2 4 8 9 5 10 11 3 6 12 13 7 14 15
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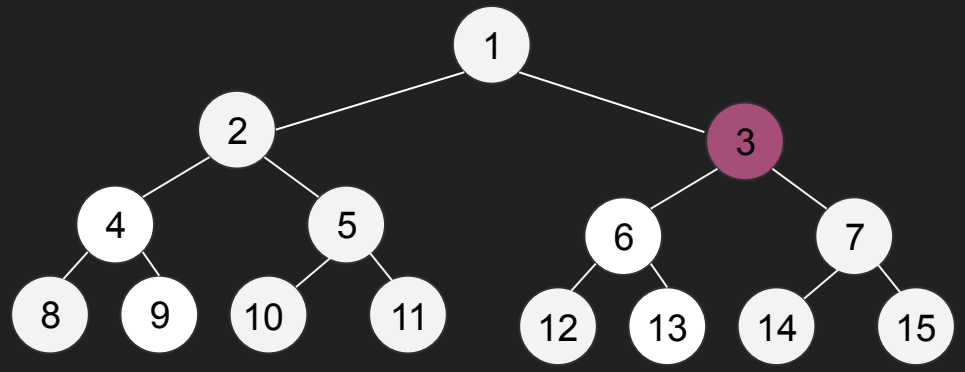
Tree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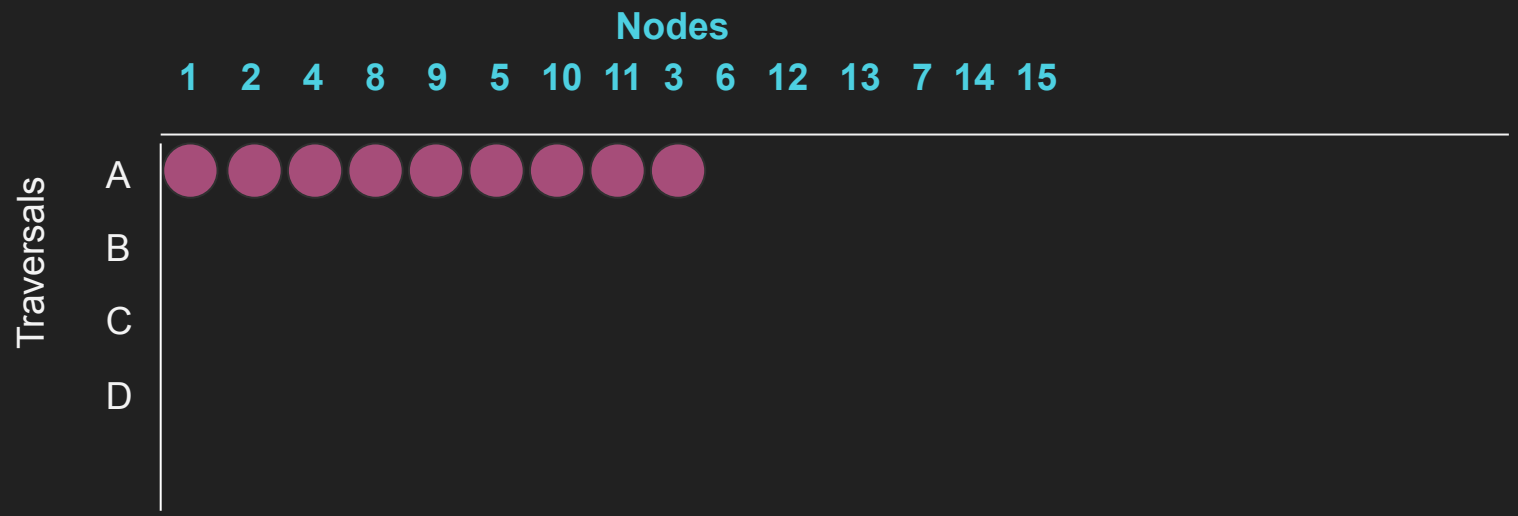
Nodes
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Traversals
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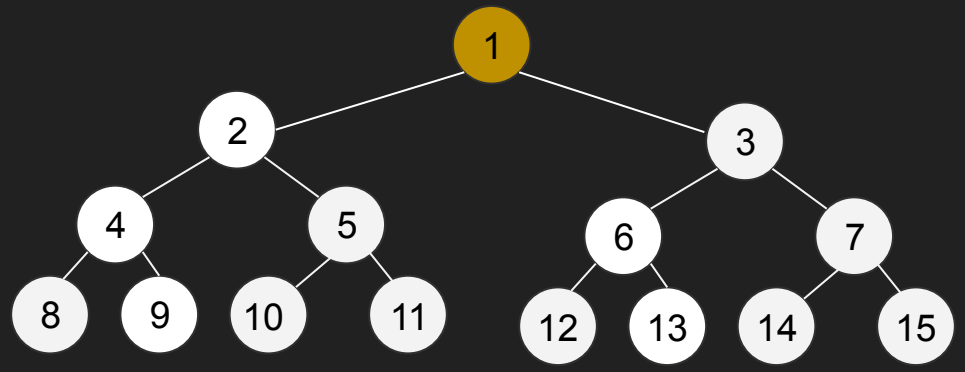
D

Tree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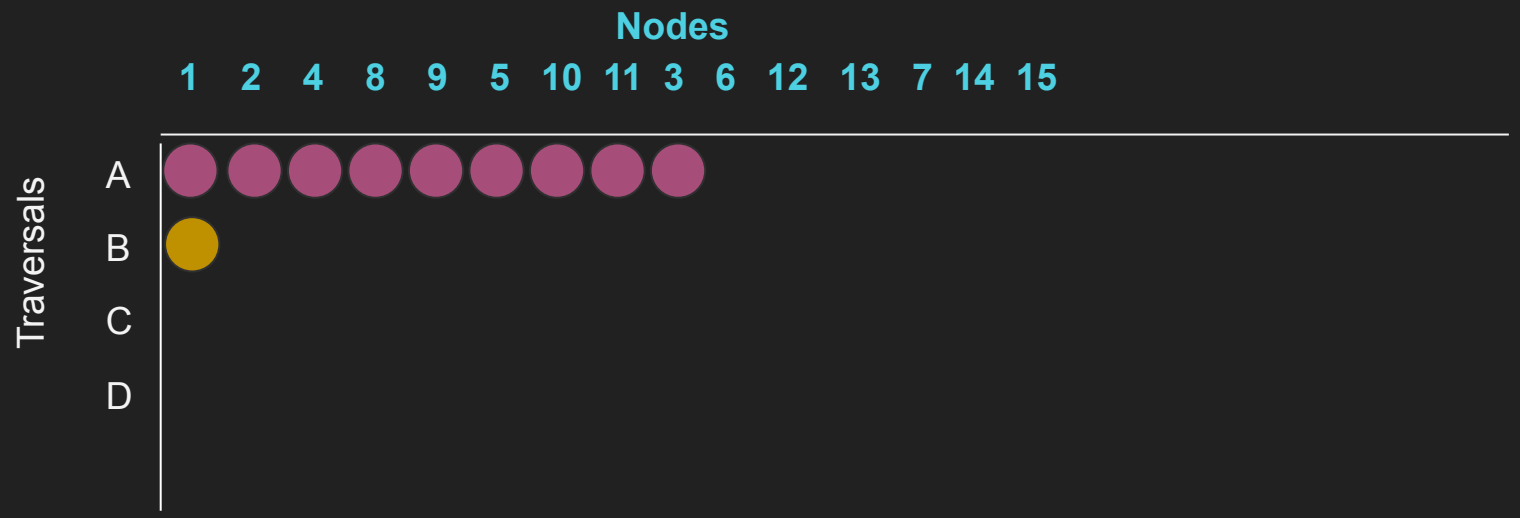
Nodes
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Traversals
A
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C
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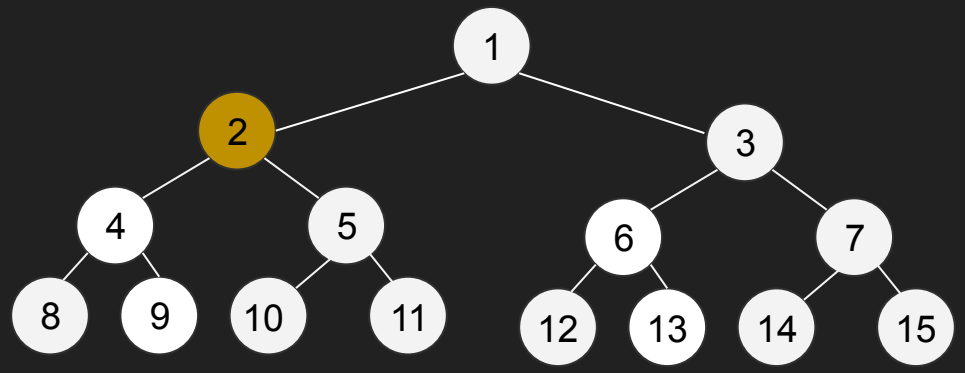
Tree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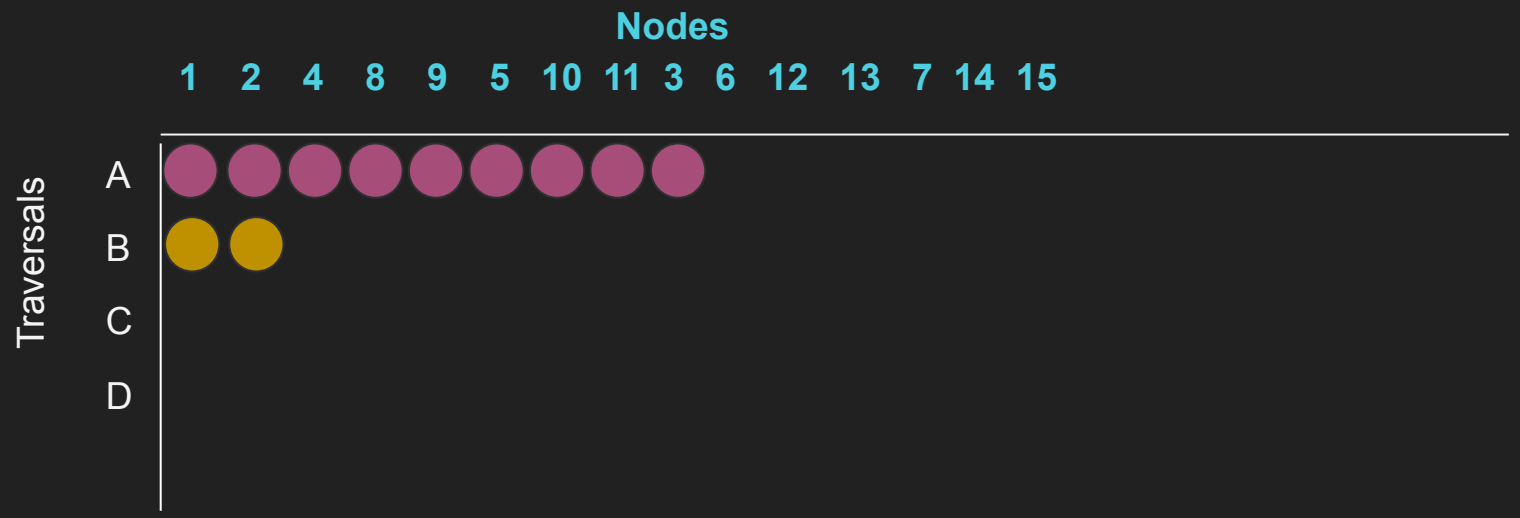
Nodes
1 2 4 8 9 5 10 11 3 6 12 13 7 14 15
Traversals
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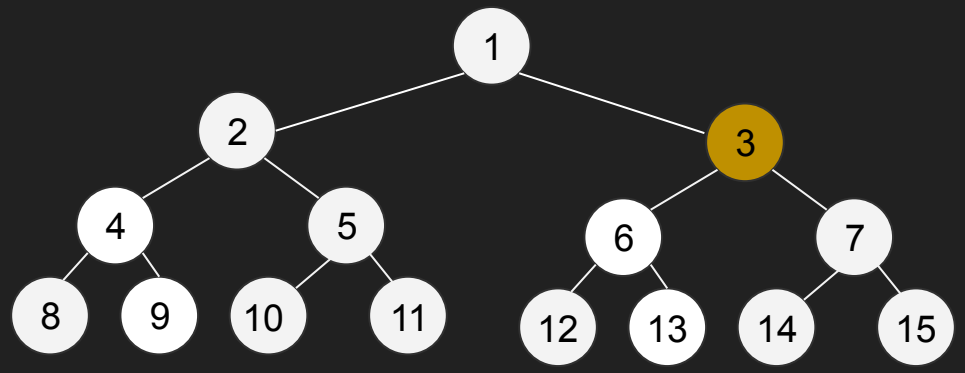
Tree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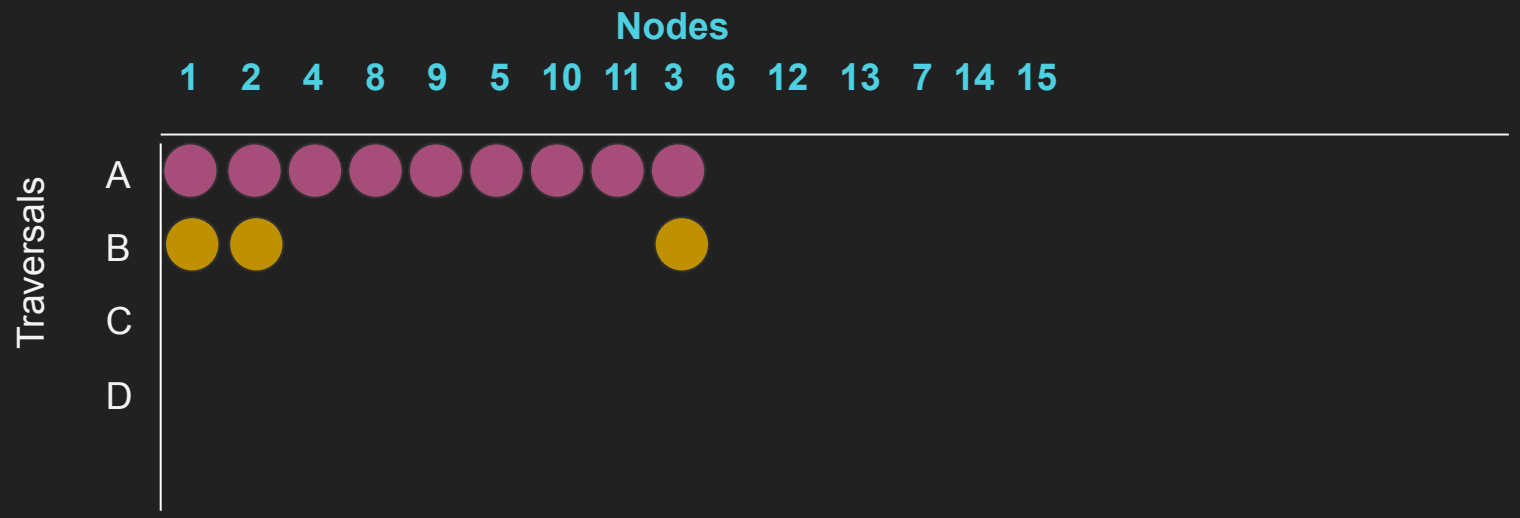
Nodes
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Traversals
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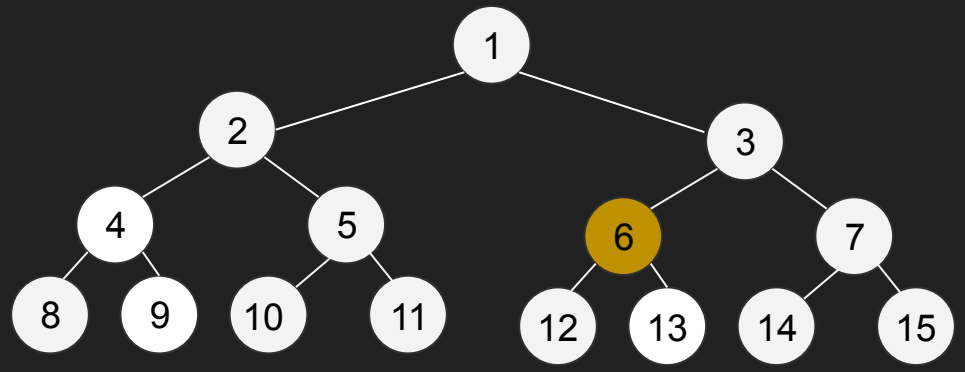
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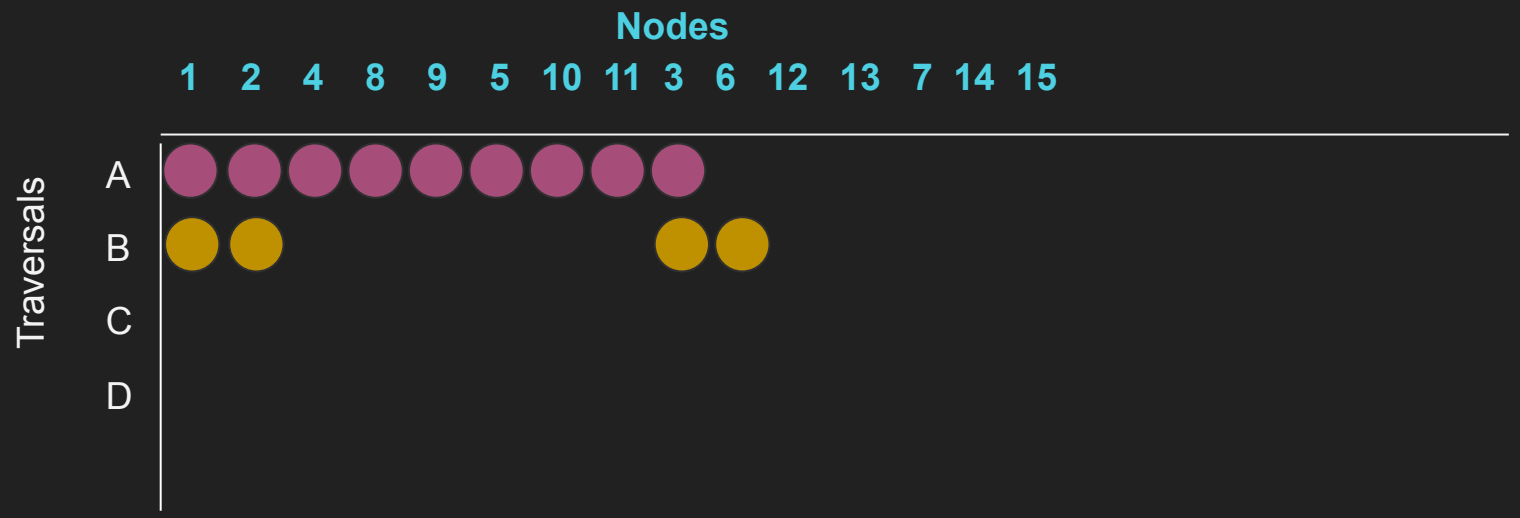
Nodes
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Traversals
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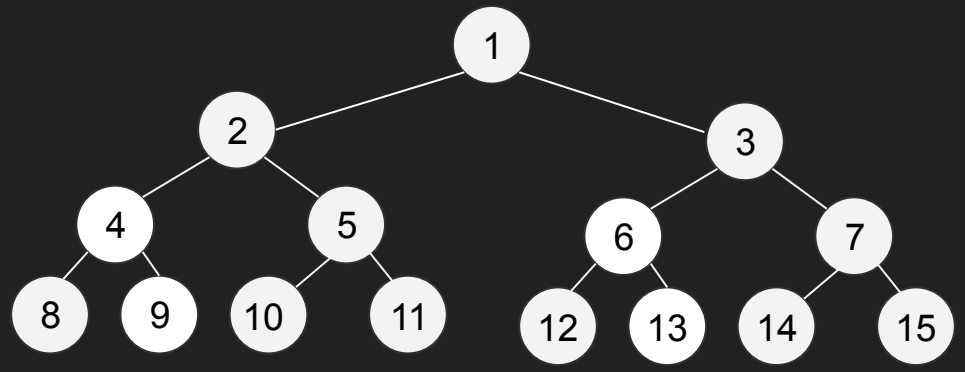
Tree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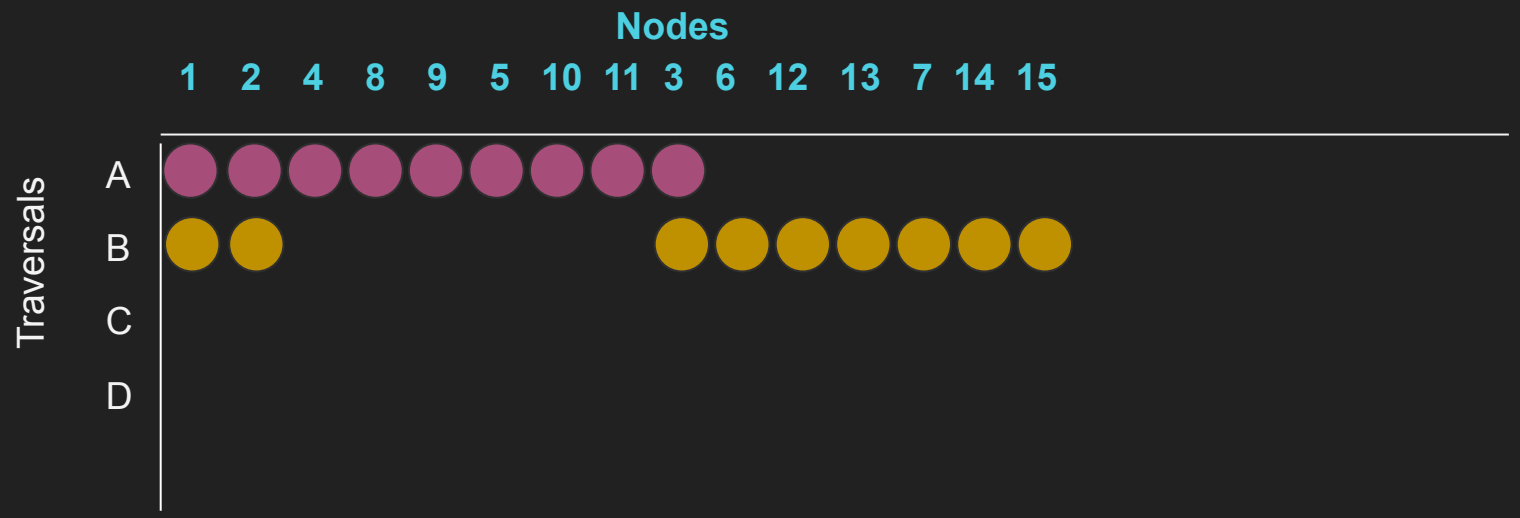
Nodes
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Traversals
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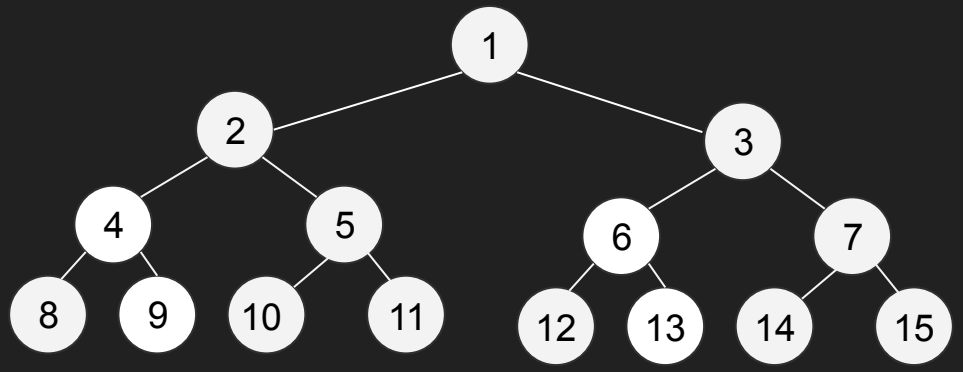
Tree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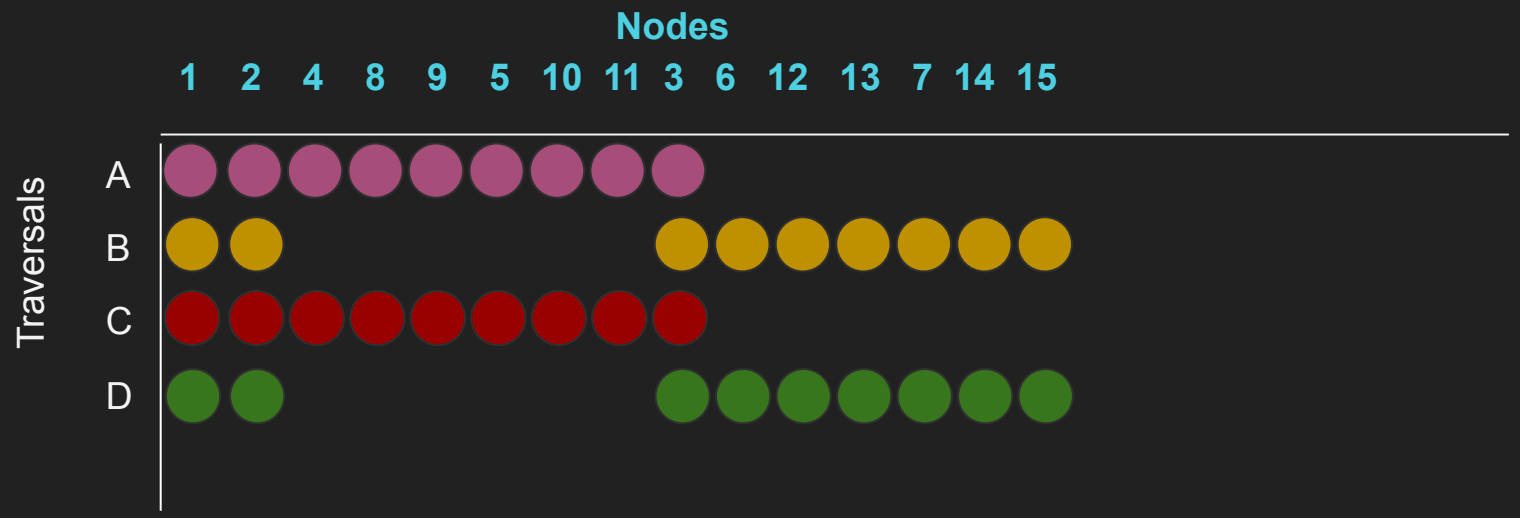
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Traversals
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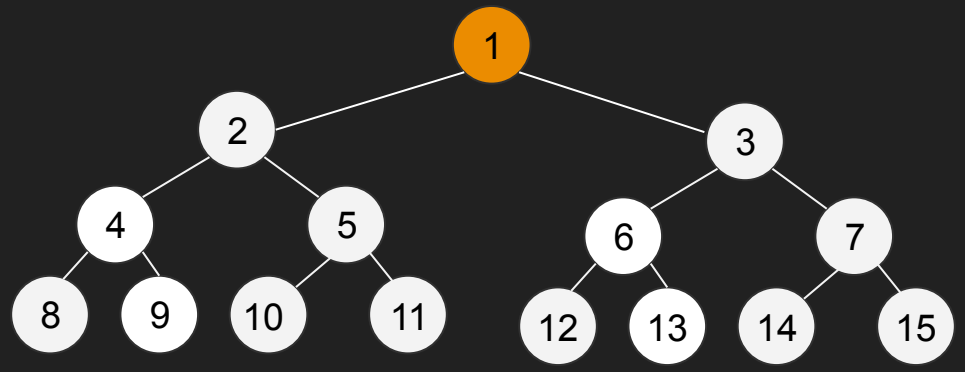
Tree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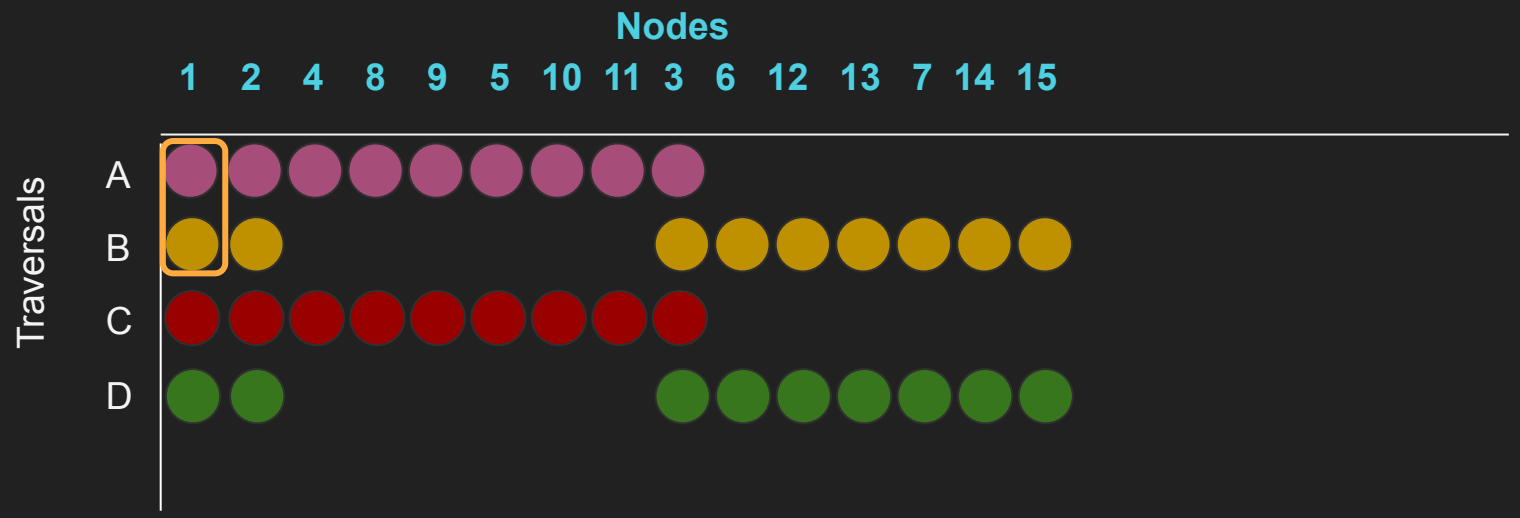
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Traversals
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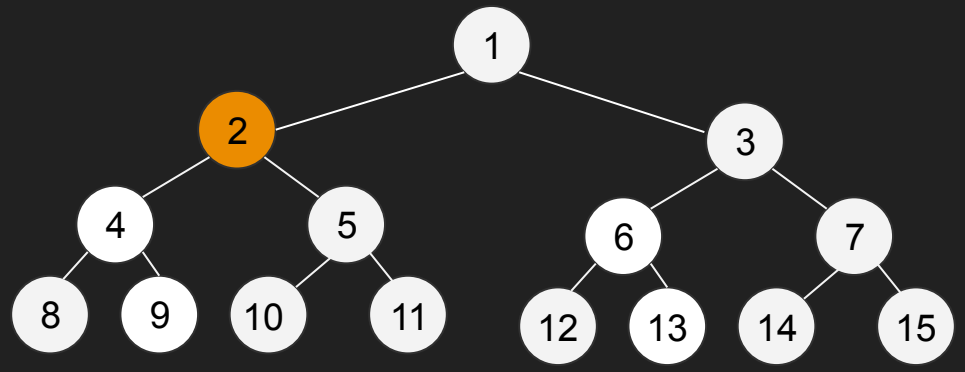
Tree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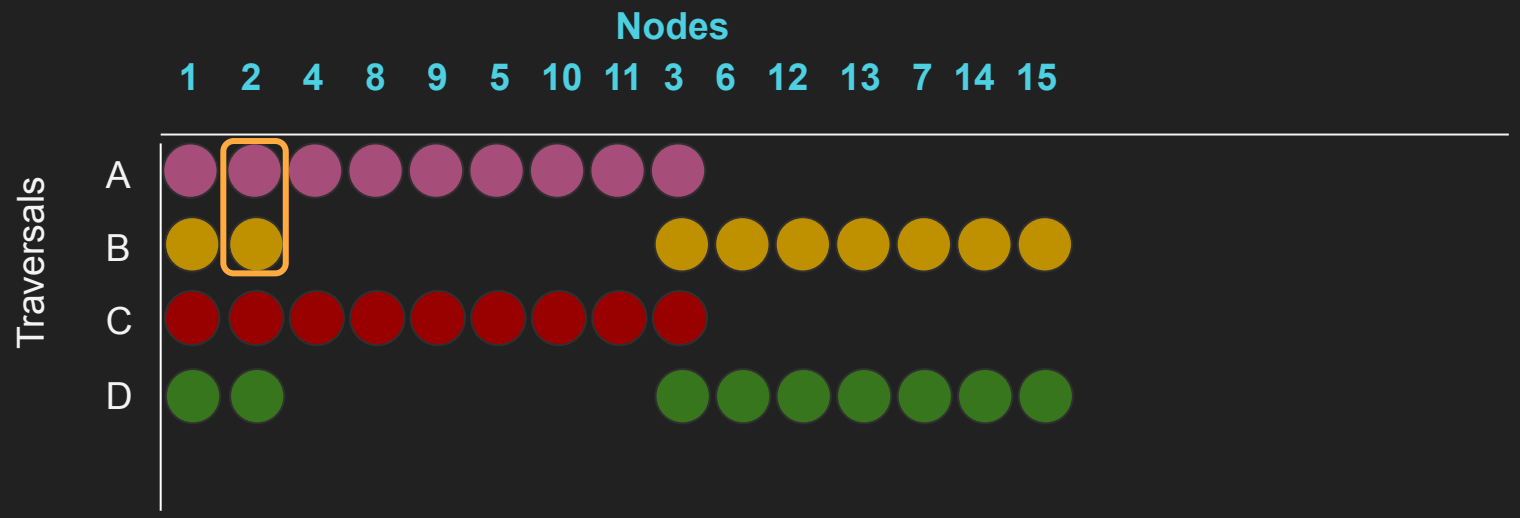
Nodes
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Traversals
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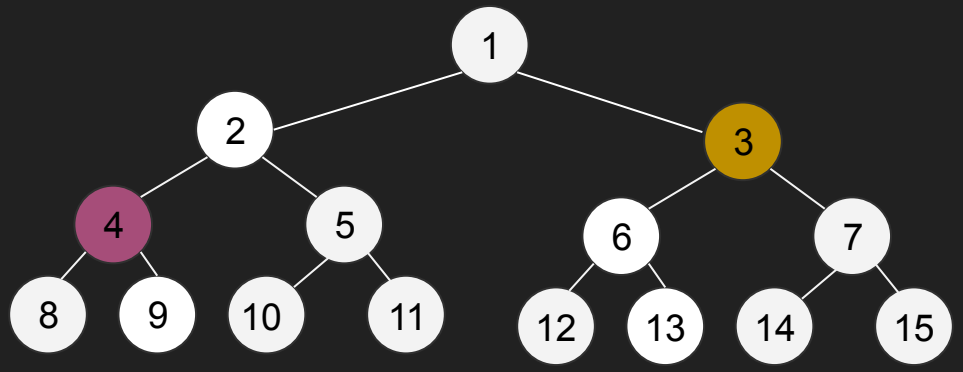
Tree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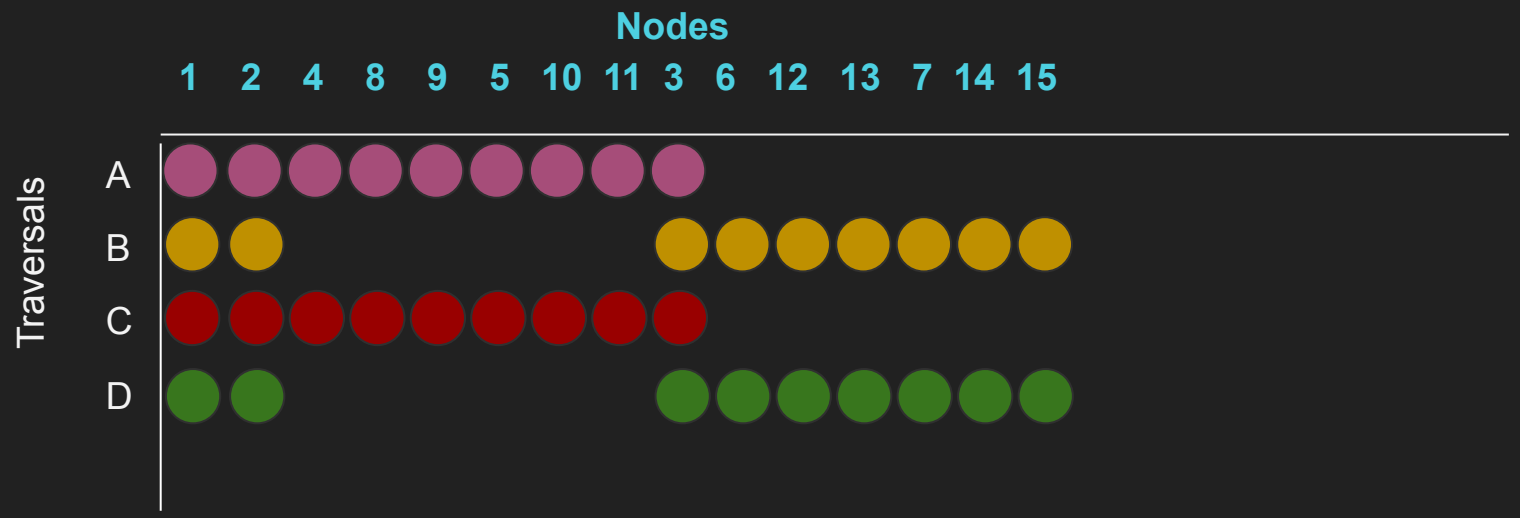
Nodes
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Traversals
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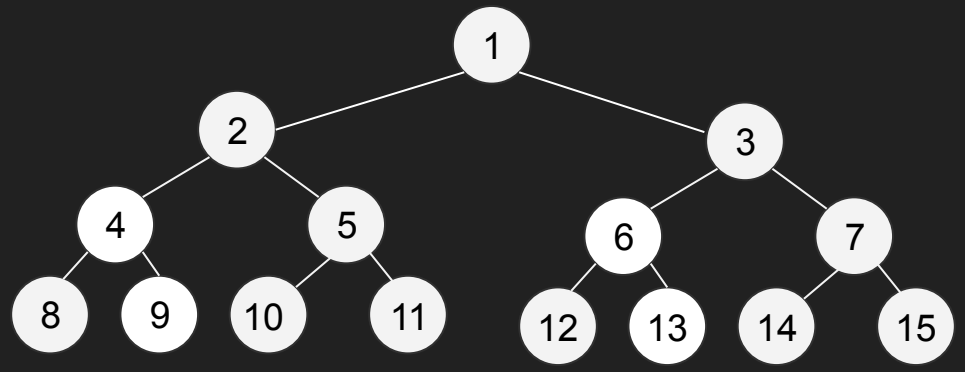
Tree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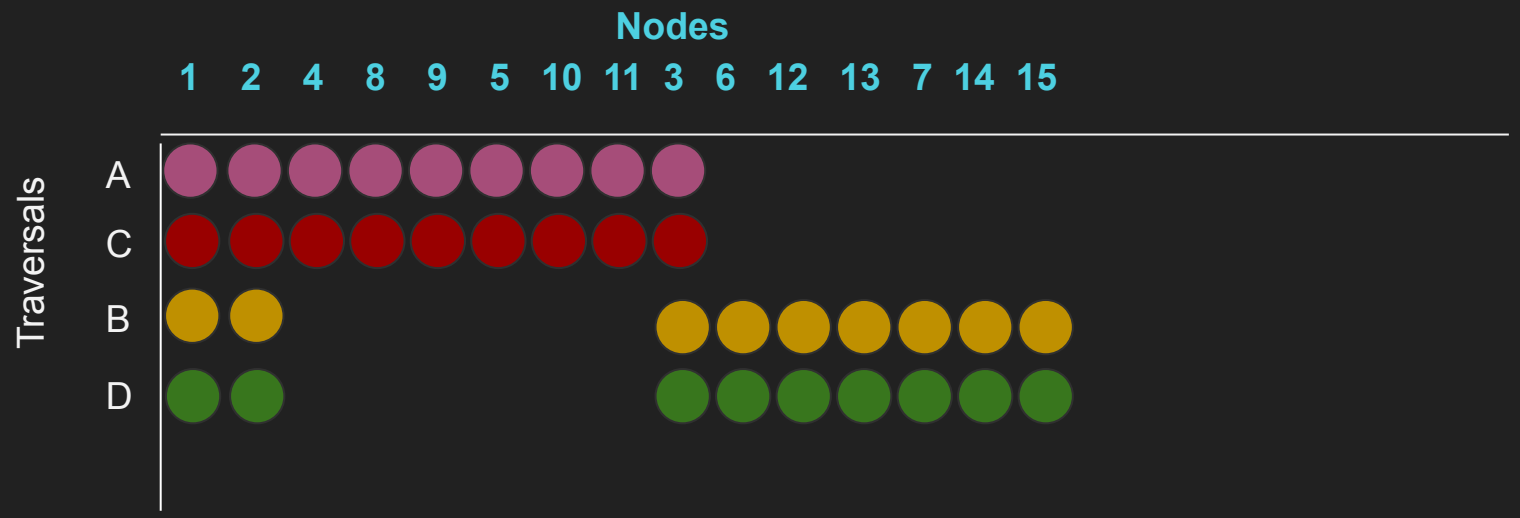
Nodes
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Traversals
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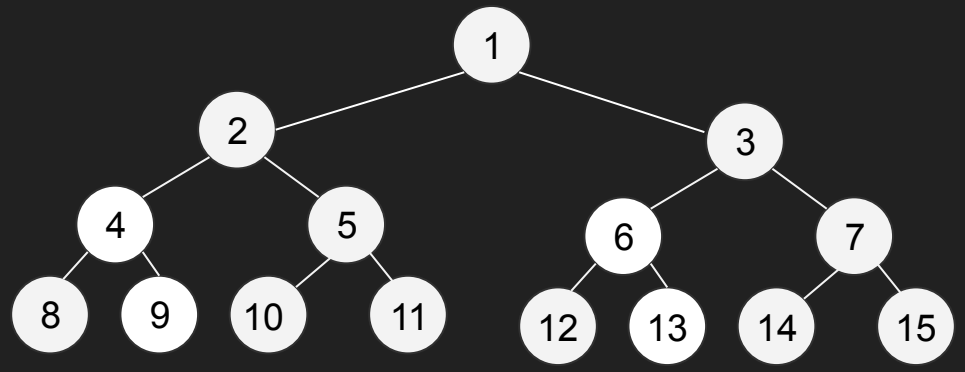
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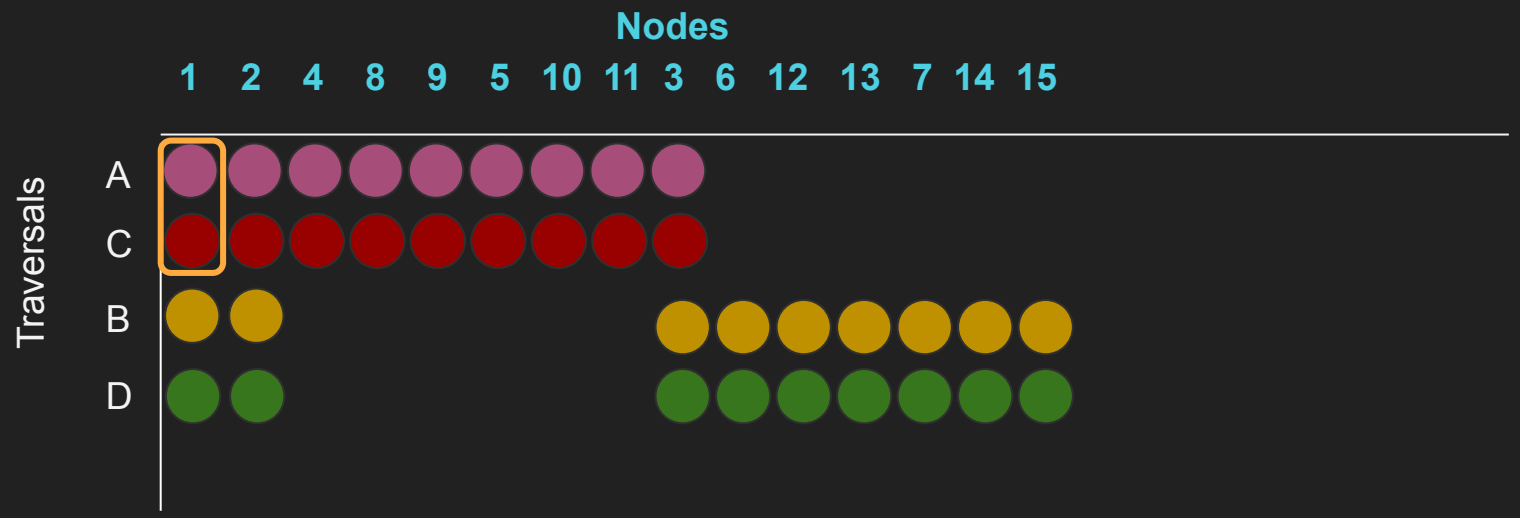
Nodes
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Traversals
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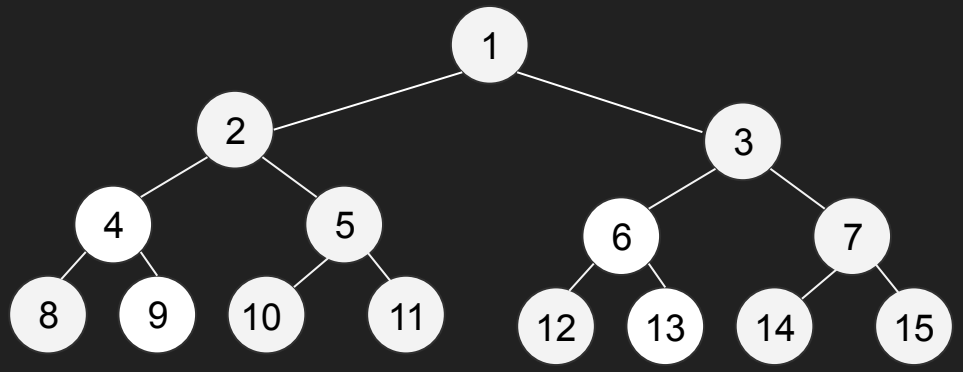
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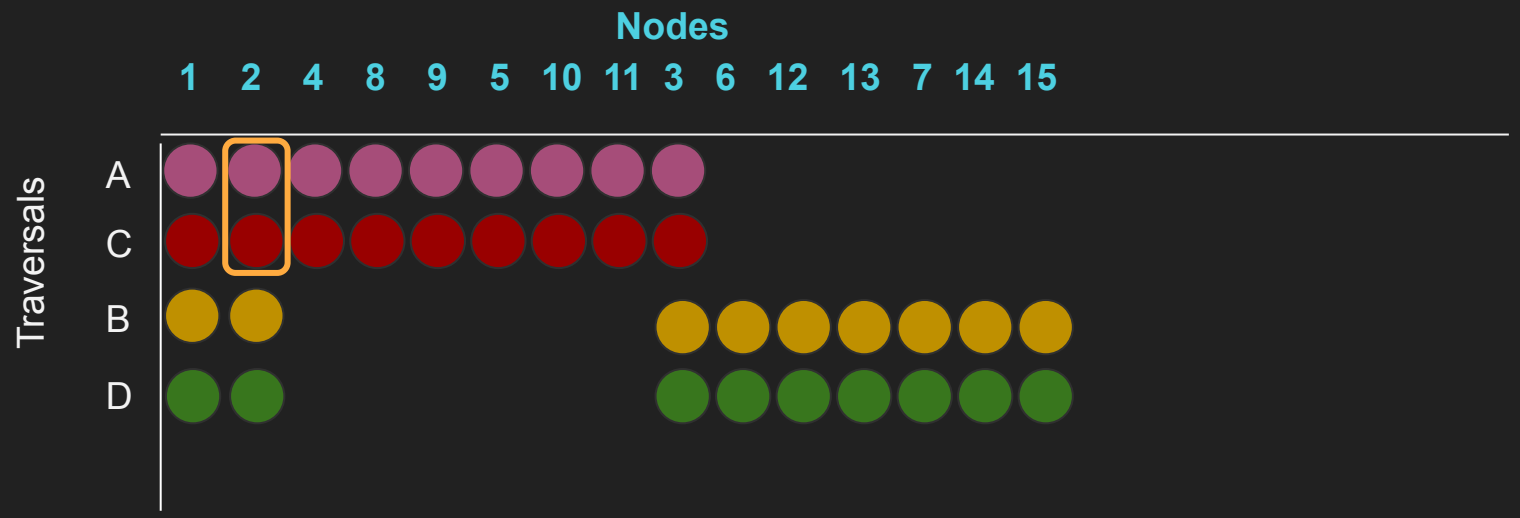
Nodes
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Traversals
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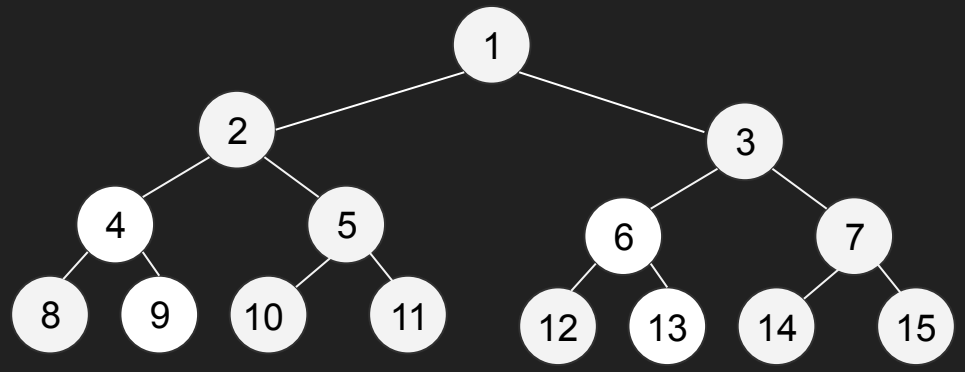
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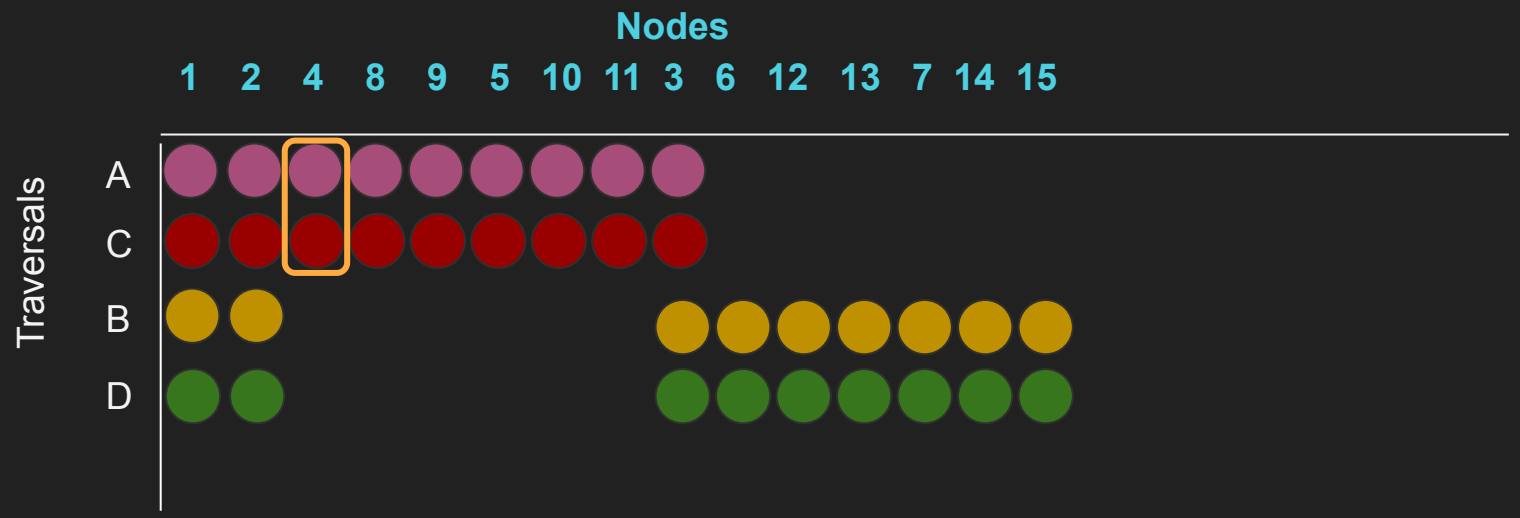
Nodes
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Traversals
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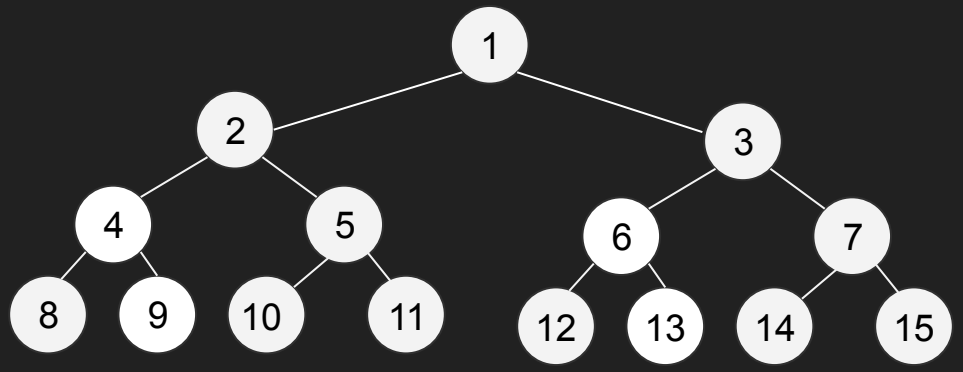
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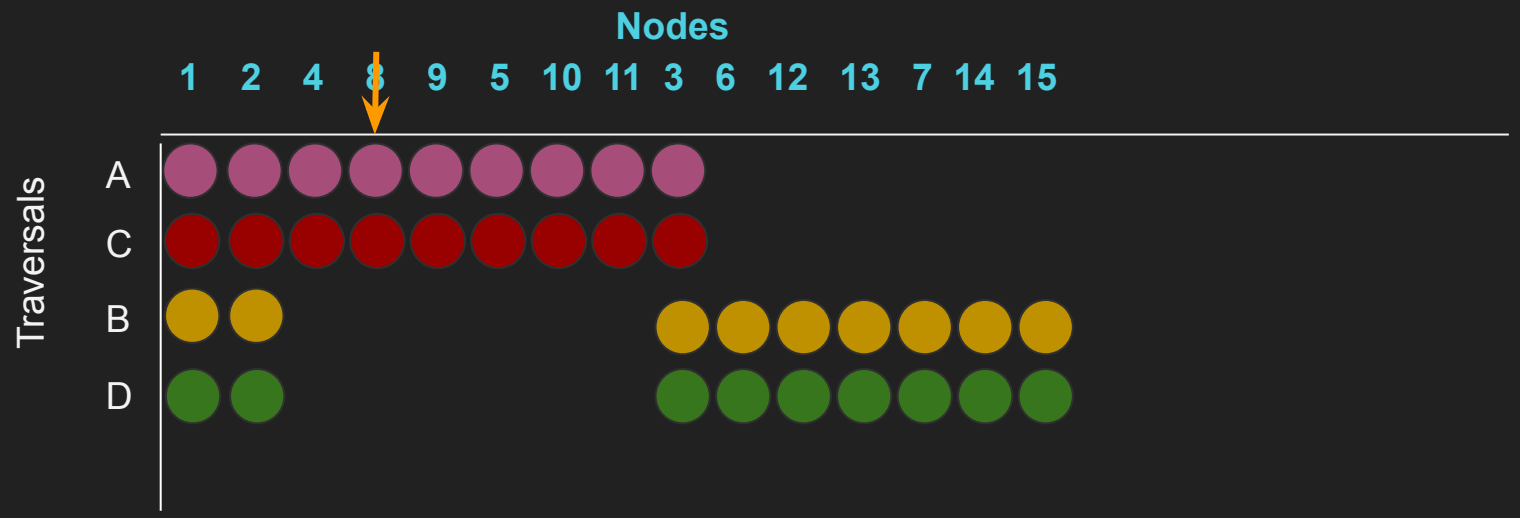
Nodes
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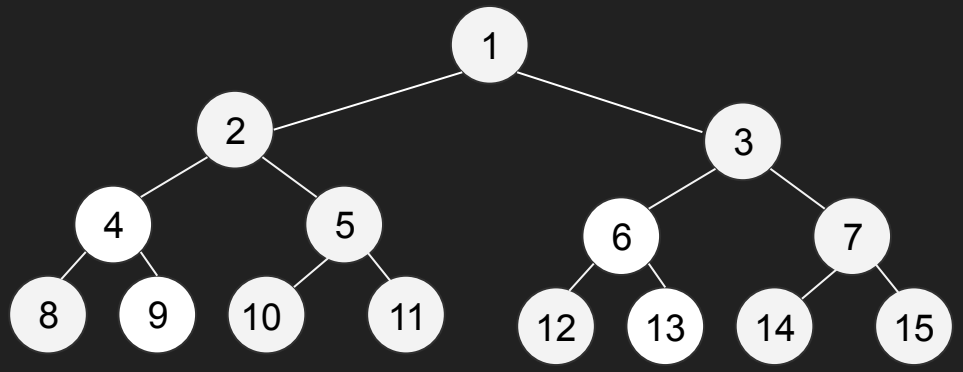
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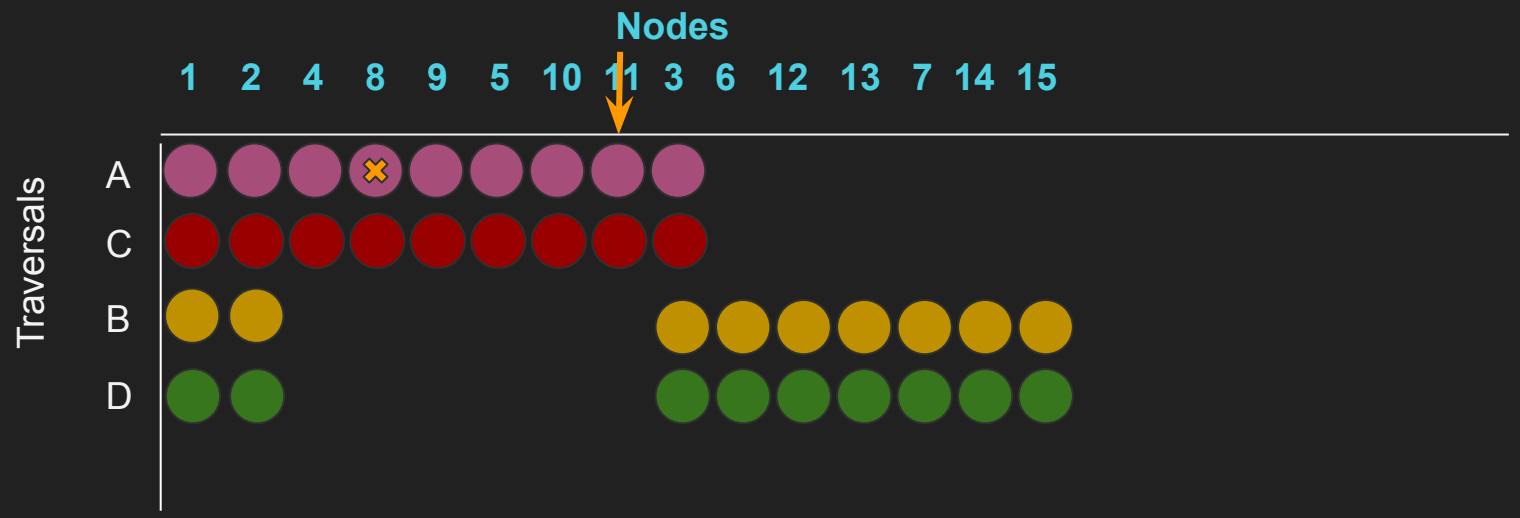
Nodes
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Traversals
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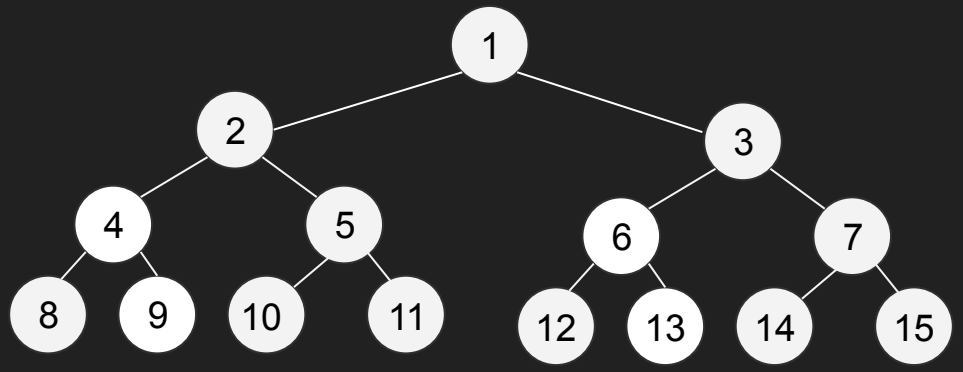
Tree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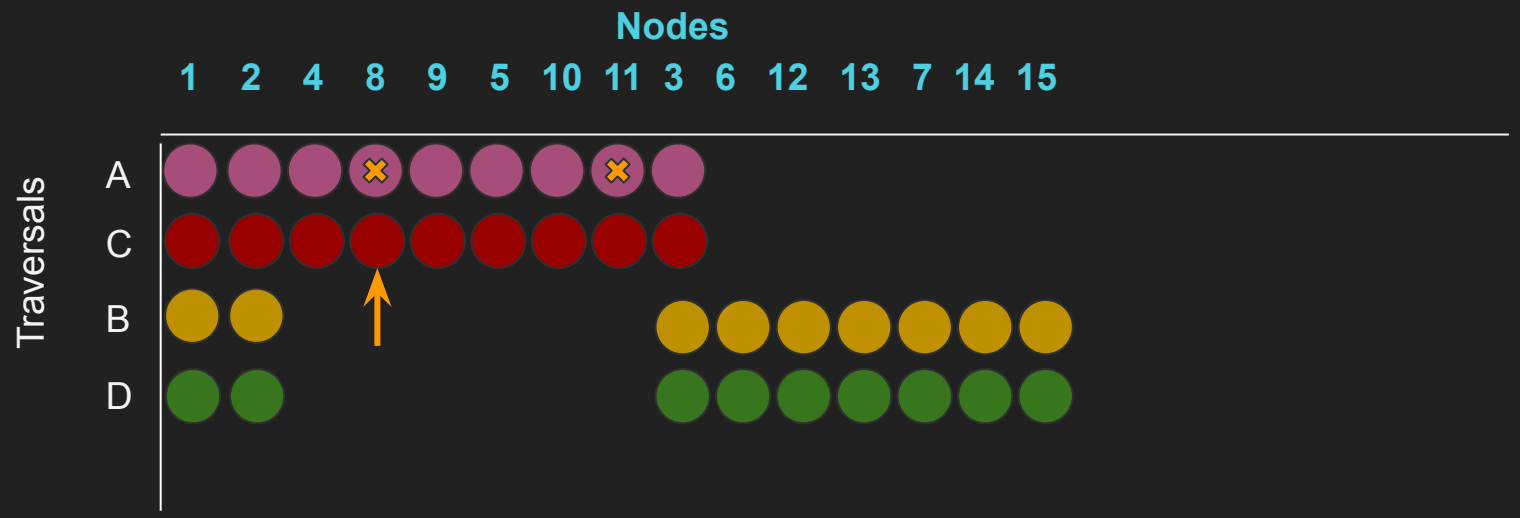
Nodes
1 2 4 8 9 5 10 11 3 6 12 13 7 14 15
Traversals
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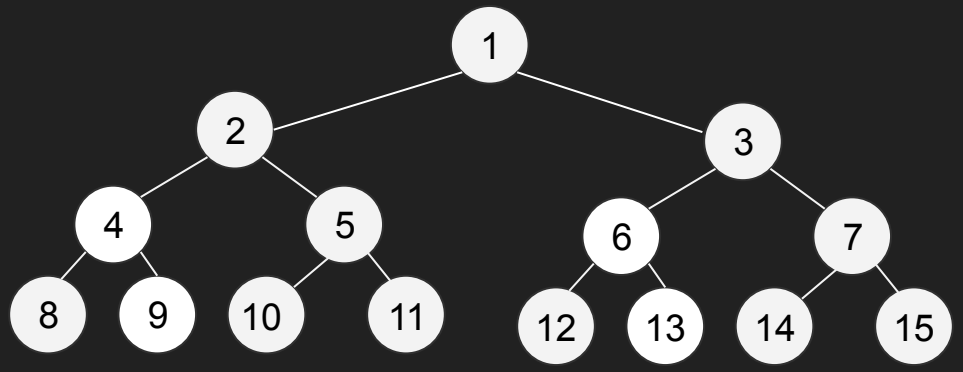
Tree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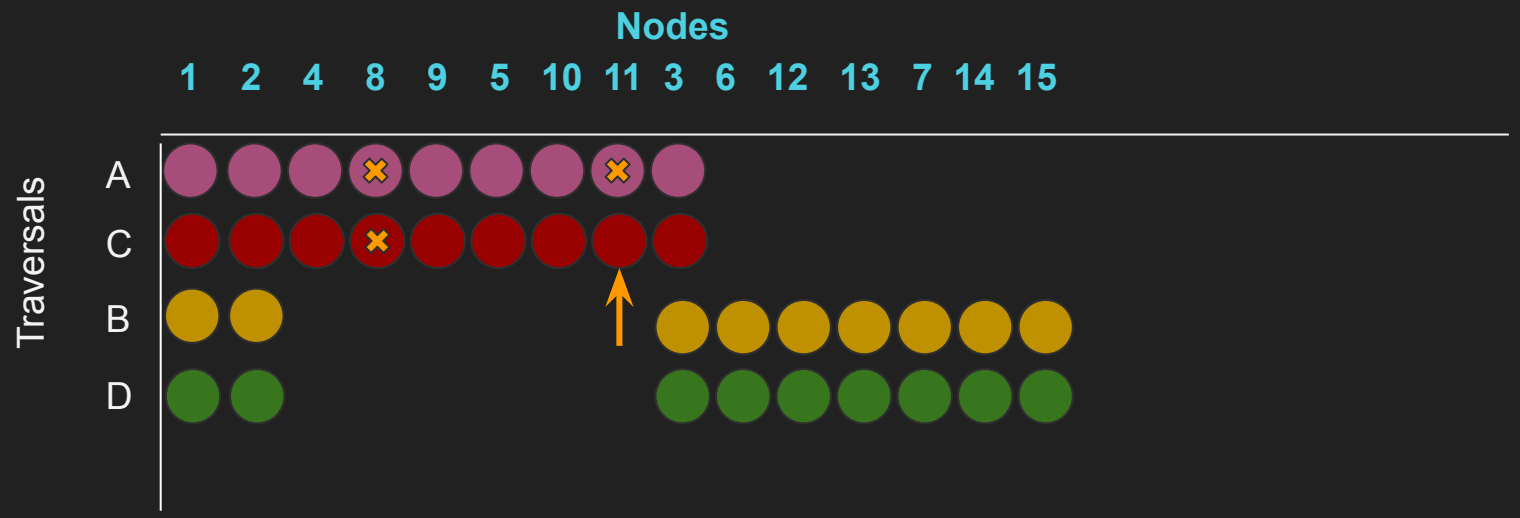

Nodes
1 2 4 8 9 5 10 11 3 6 12 13 7 14 15
Traversals
A
C
B
D

Milind Kulkarni’s Group at Purdue

Dynamic Vectorization

Dynamic Factorization

OPEN PROBLEM

Serial Reduction

```
int reduce_serial(int x) {
  assert(x > 0 && !(x % 2));
  int finish_time = 0;
  while (true) {
    if (!x) {
      break;
    }
    x = x - 2;
    ++finish_time;
  }
  return finish_time;
}
```

Clobber to Disable the Optimizer Locally

```
int reduce_serial(int x) {
  assert(x > 0 && !(x % 2));
  int finish_time = 0;
  while (true) {
    clobber();
    if (!x) {
      break;
    }
    x = x - 2;
    ++finish_time;
  }
  return finish_time;
}
```

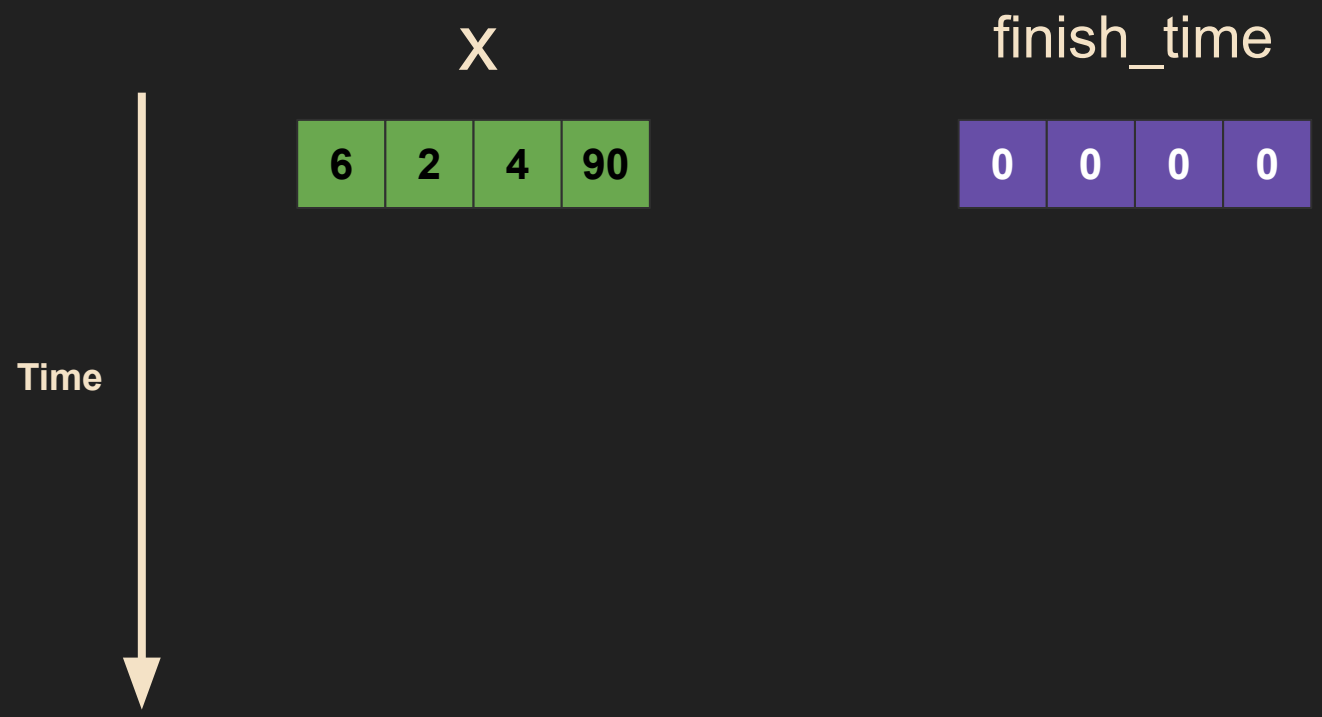
Clobber

```
void clobber() {
  asm volatile(“” : : : “memory”);
}
```

Serial Reduction

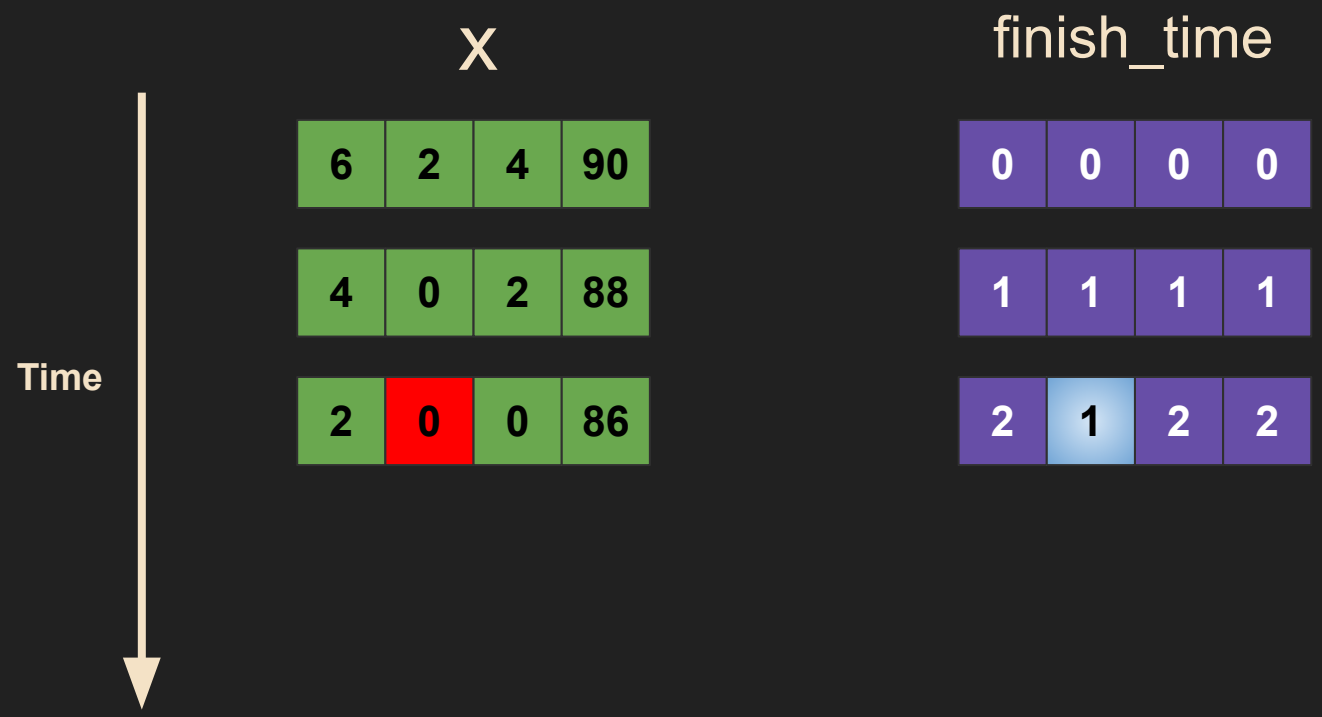
```
int run_serial(int *in, int *out, int len) {
  for (int i = 0; i < len; ++i) {
    out[i] = reduce_serial(in[i]);
  }
}
```

Statically Vectorized Reduction

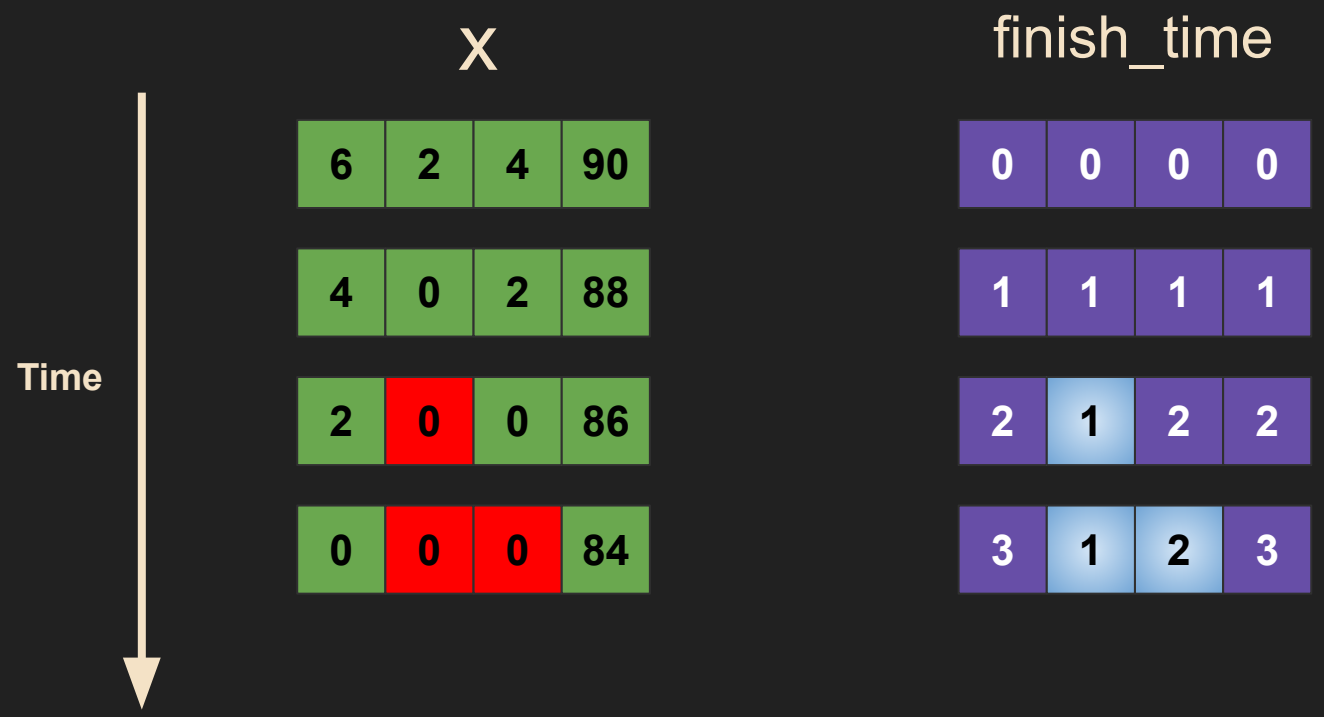


Statically Vectorized Reduction

Statically Vectorized Reduction



Statically Vectorized Reduction



Statically Vectorized Reduction

Statically Vectorized Reduction

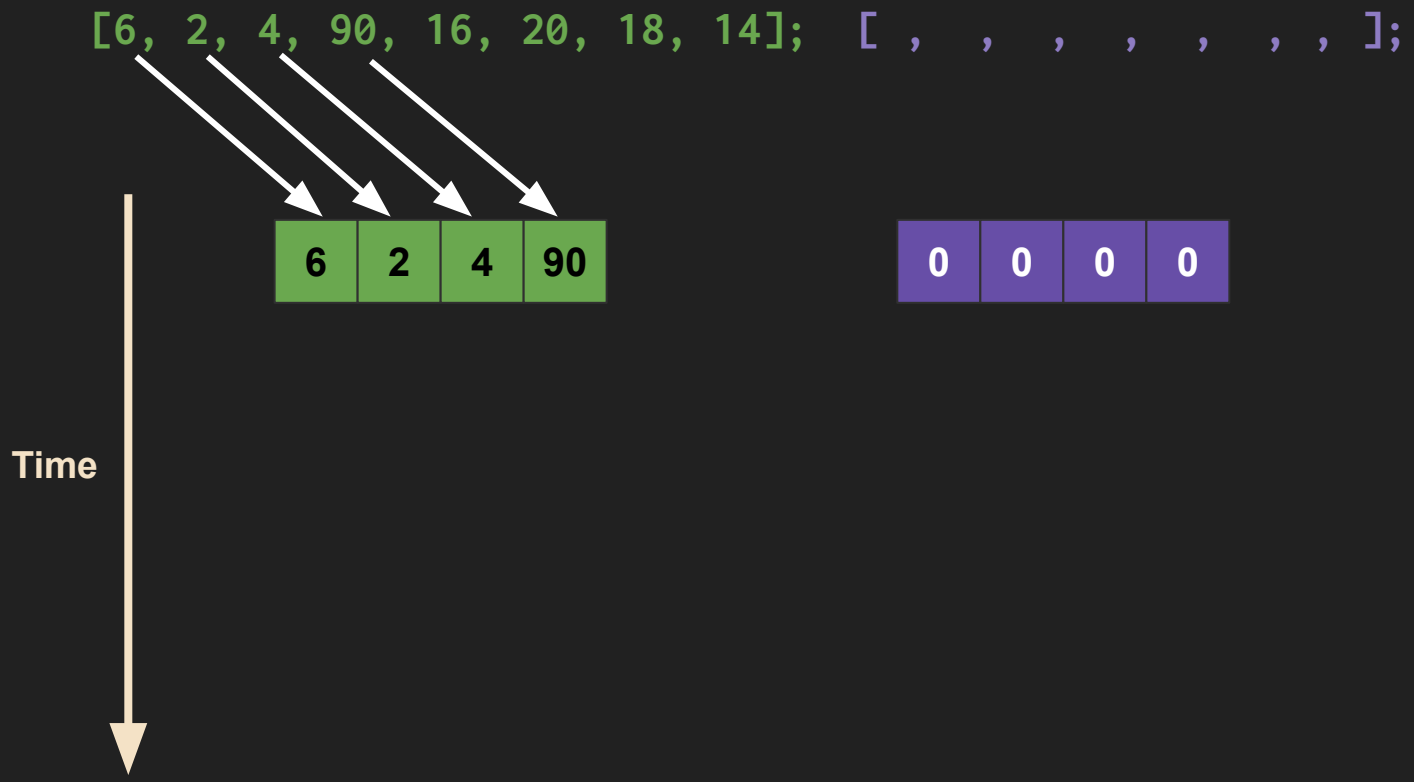
```
int4 reduce_vec(int4 x) {
  int4 finish_time(0);
  while (true) {
    int4 mask = x > int4(0);
    if (mask.are_all_zeroes())
      break;
    x = x - 2;
    finish_time = finish_time - mask;
  }
  return finish_time;
}
```

Statically Vectorized Reduction

Dynamically Vectorized Reduction

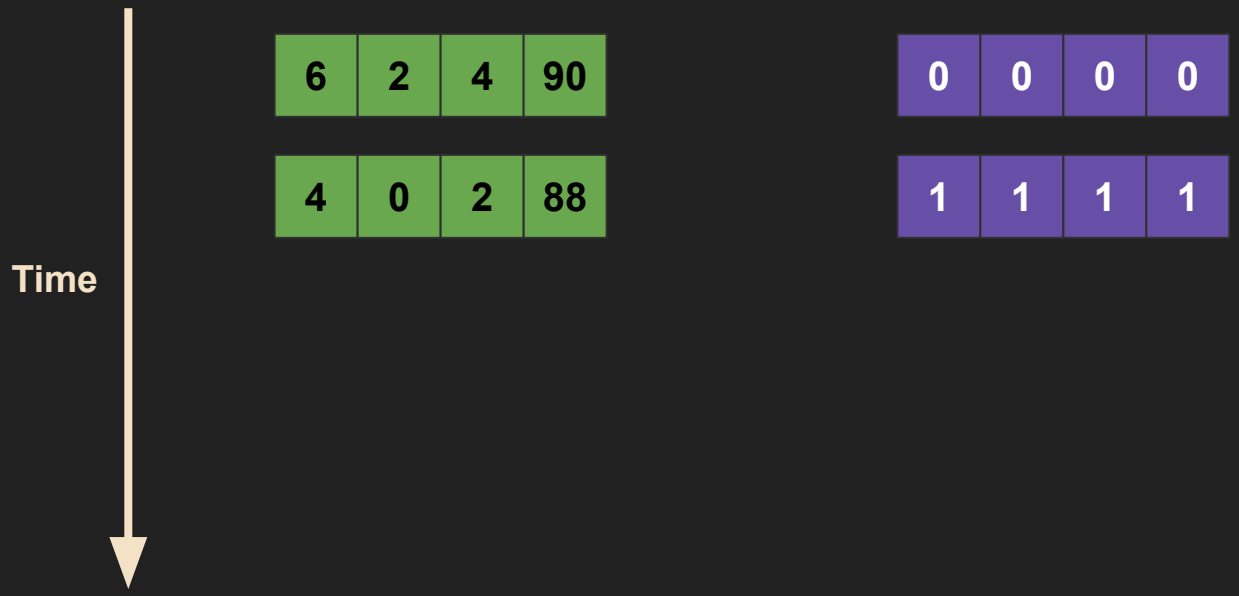
```
[6, 2, 4, 90, 16, 20, 18, 14];  [ ,  ,  ,  ,  ,  , , ];
```

Dynamically Vectorized Reduction



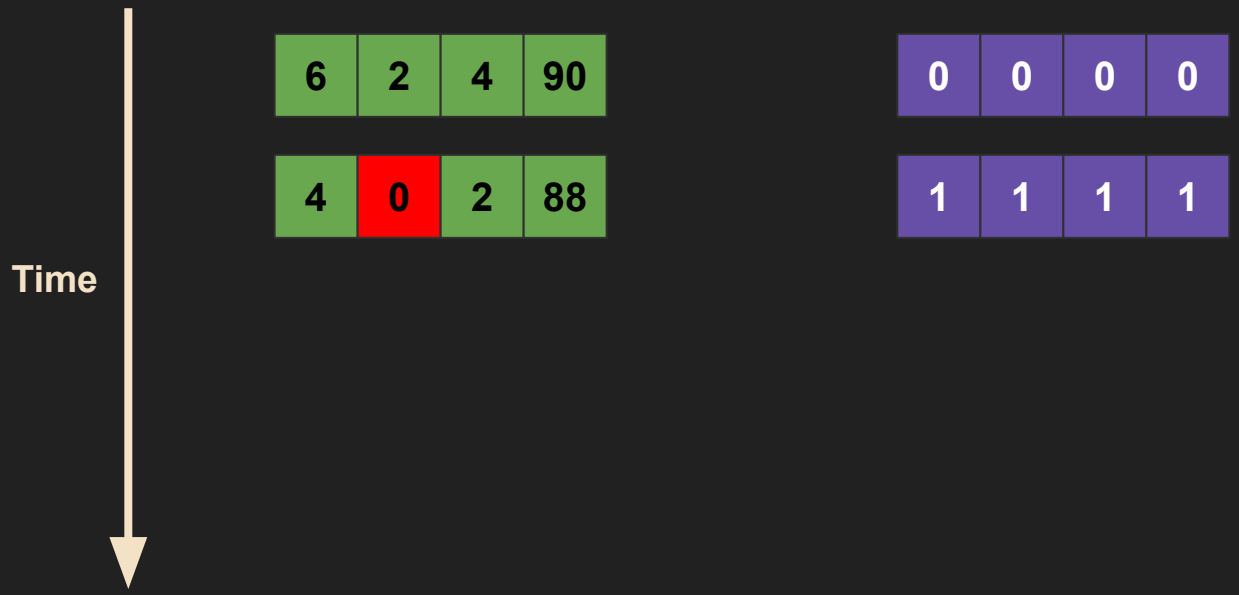
Dynamically Vectorized Reduction

```
[6, 2, 4, 90, 16, 20, 18, 14];  [ ,  ,  ,  ,  ,  , , ];
```



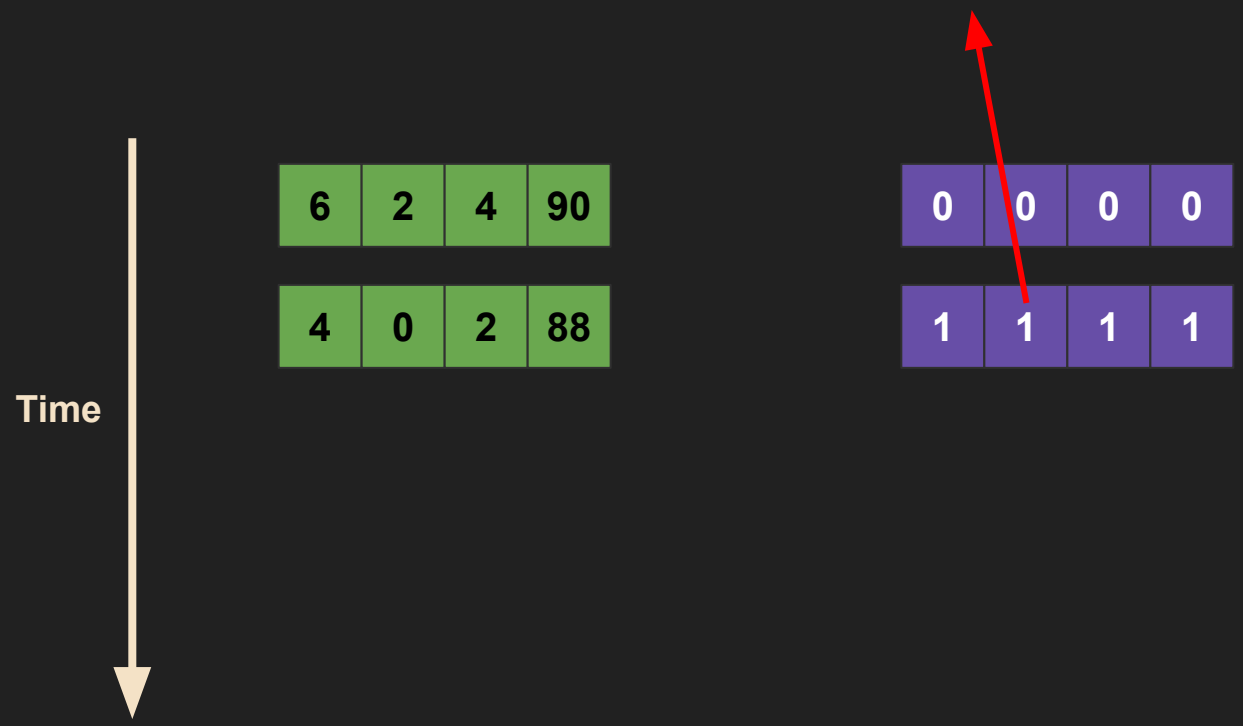
Dynamically Vectorized Reduction

```
[6, 2, 4, 90, 16, 20, 18, 14];  [ ,  ,  ,  ,  ,  , , ];
```

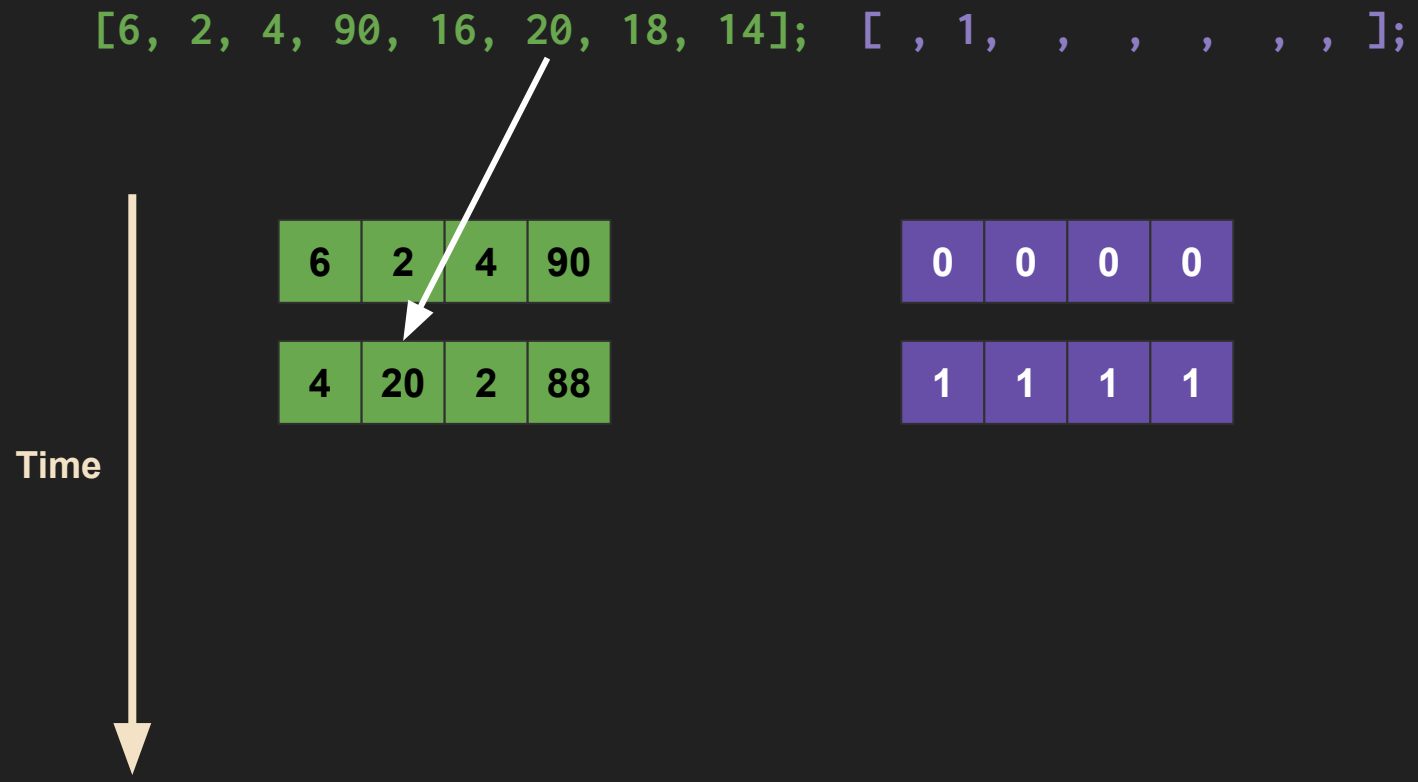


Dynamically Vectorized Reduction

```
[6, 2, 4, 90, 16, 20, 18, 14];  [ , 1,  ,  ,  ,  , , ];
```

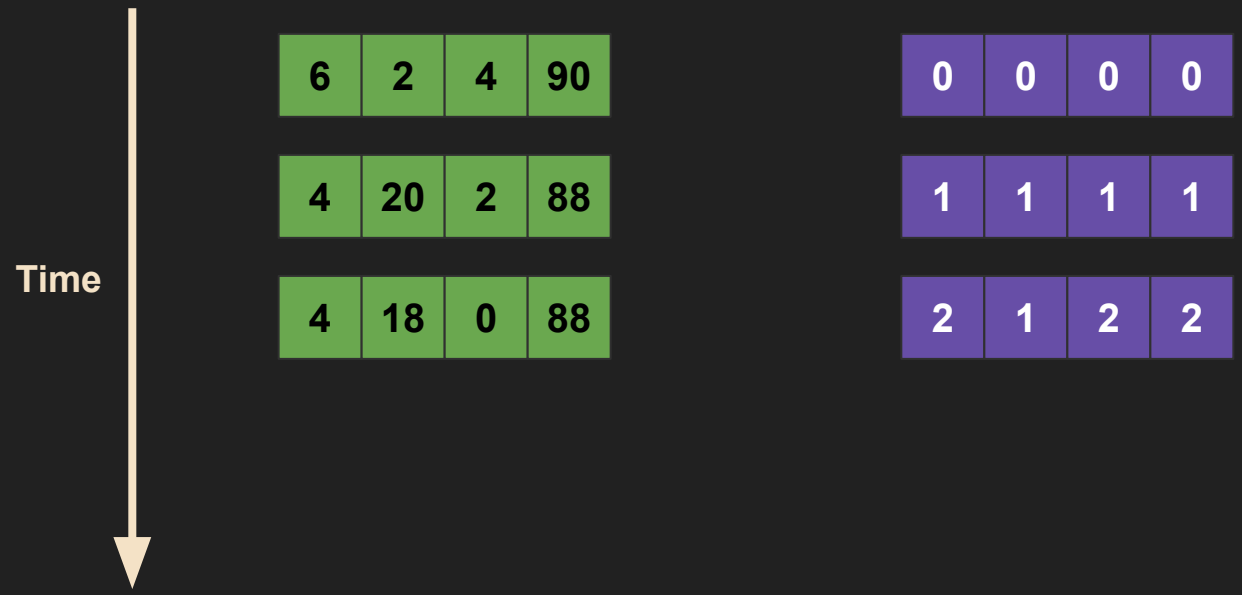


Dynamically Vectorized Reduction



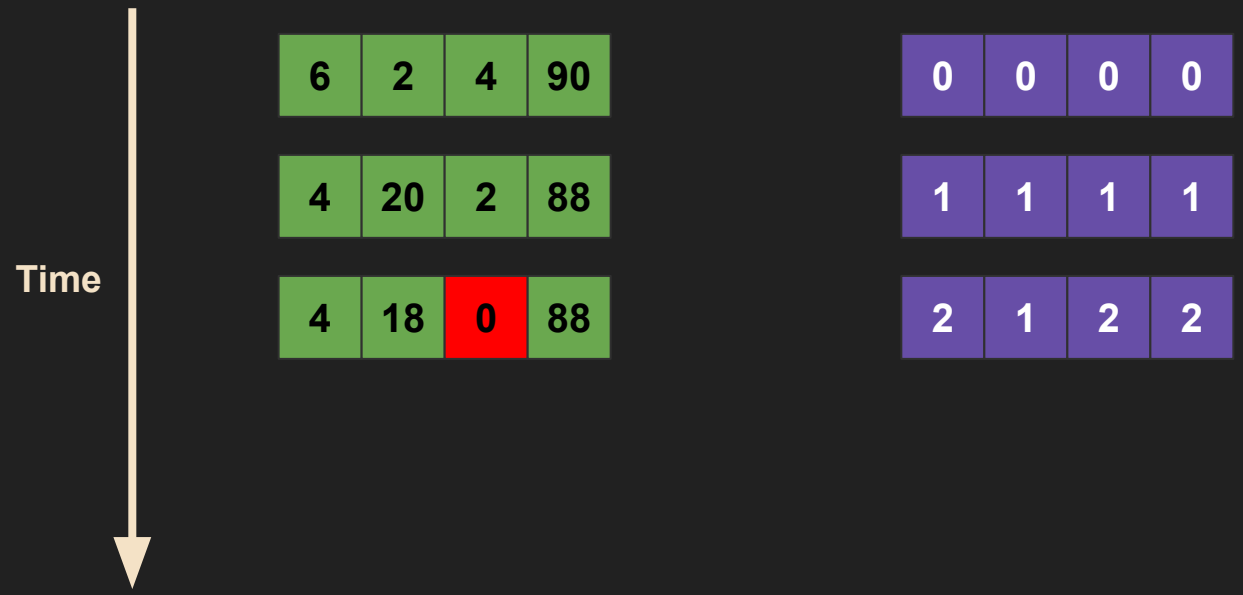
Dynamically Vectorized Reduction

```
[6, 2, 4, 90, 16, 20, 18, 14];  [ , 1,  ,  ,  ,  , , ];
```



Dynamically Vectorized Reduction

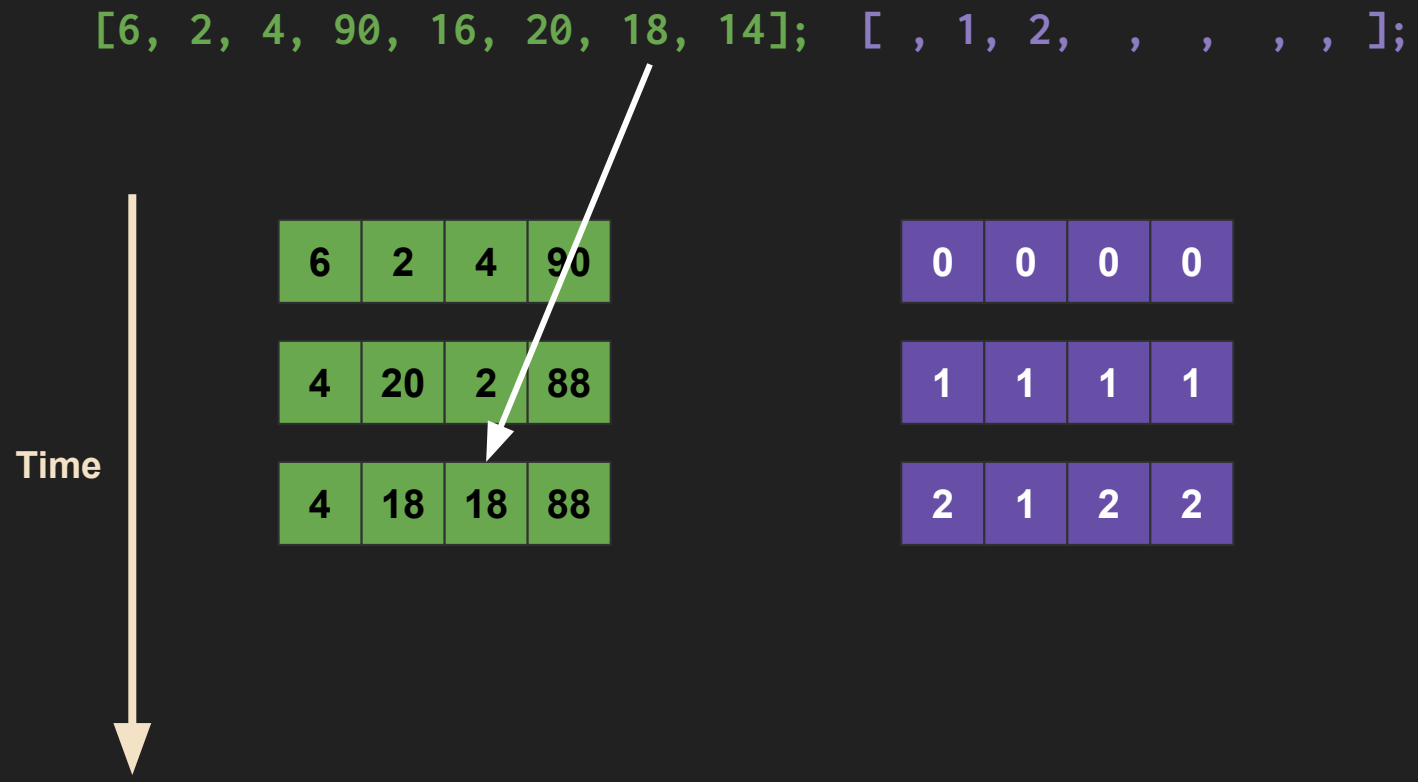
```
[6, 2, 4, 90, 16, 20, 18, 14];  [ , 1,  ,  ,  ,  , , ];
```



Dynamically Vectorized Reduction

```
[6, 2, 4, 90, 16, 20, 18, 14];  [ , 1, 2,  ,  ,  , , ];
```

Dynamically Vectorized Reduction




HOW FAST
IS IT?

1.25x faster than statically vectorized

Thank You!

Thanks to:

- Liberty Research Group at Princeton
- Dr. Kulkarni’s group at Purdue
- Simon Moll

for the feedback