

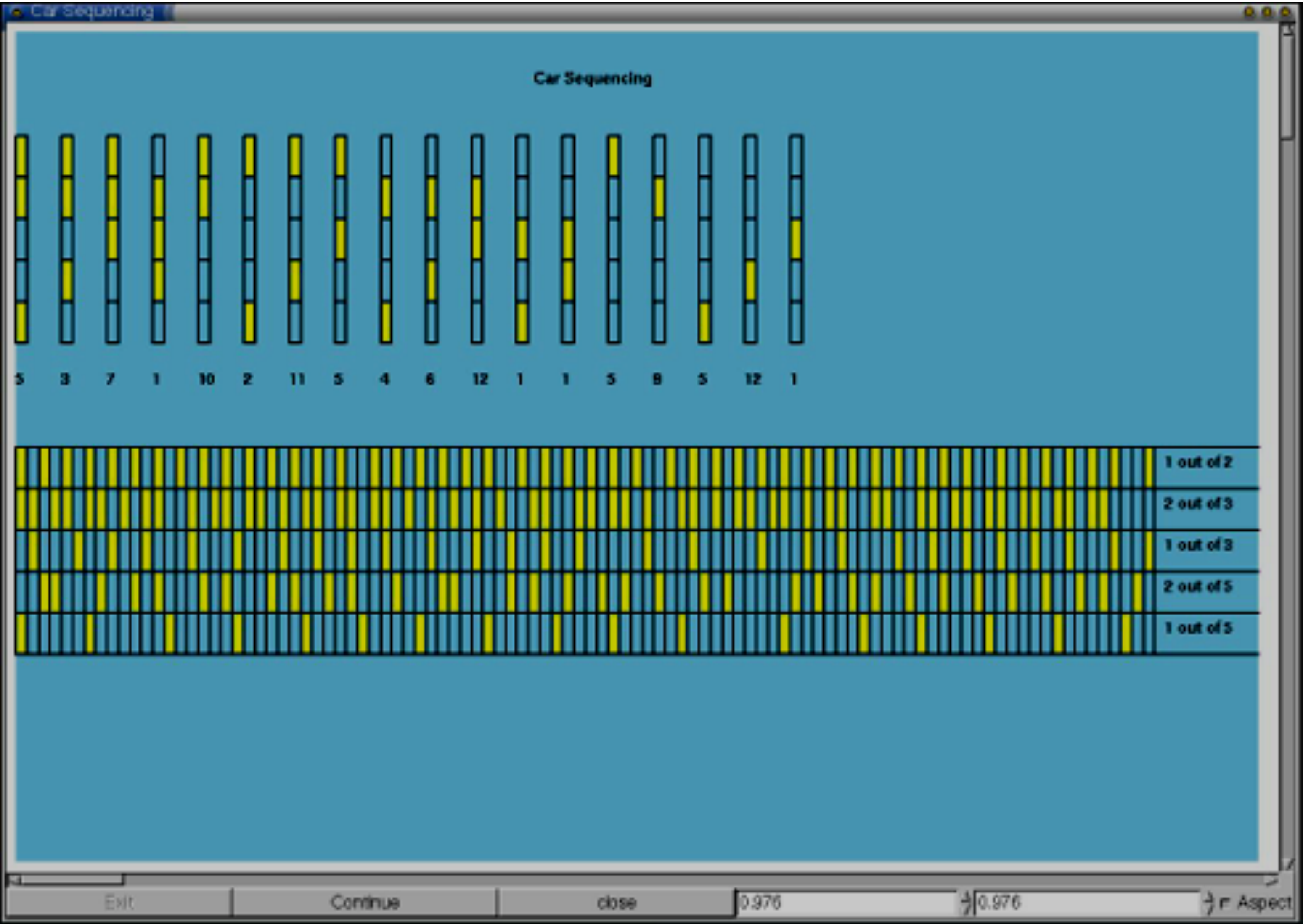
Discrete Optimization

Local Search: Part II

Goals of the Lecture

- ▶ Local search
 - swaps

Car Sequencing



Swaps

- ▶ Neighborhood
 - swap two configurations on the assembly line

Swaps

- ▶ Neighborhood
 - swap two configurations on the assembly line
- ▶ Search strategy
 - find a configuration that appears in violations
 - swap that configuration with another configuration to minimize the number of violations

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

1 1

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

1 1 1

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

3

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

3

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

3

2

Car Sequencing









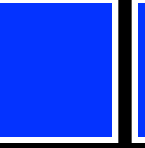

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	


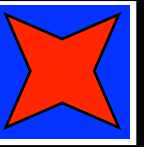
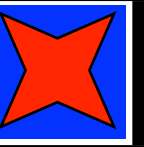
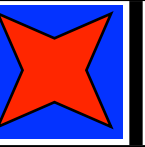
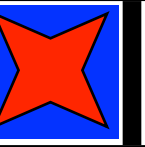
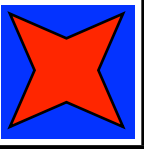
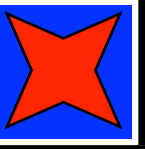
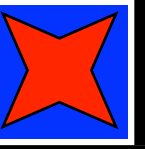
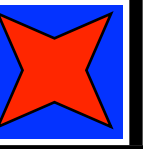



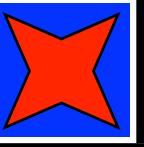



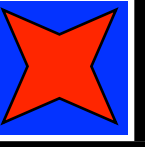
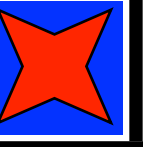
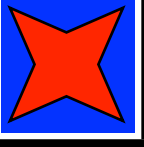
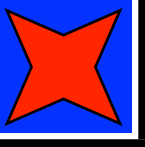
Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

3
2
2
2
3

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

3
2
2
2
3

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

3
2
2
2
3

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

1
1
0
2
0

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

1
1
0
2
0

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

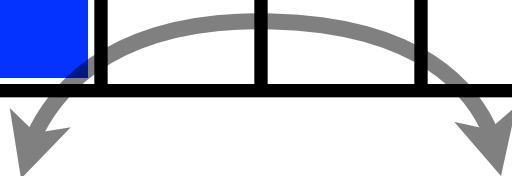
Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

1
0
0
0
0

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2



Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

1
0
0
0
0

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

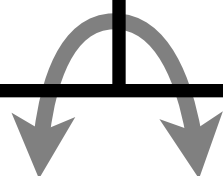
Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

1
0
0
0
0

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2



Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

1
0
0
0
0

Car Sequencing

Slots	1	2	3	4	5	6	7	8	9	10	Demand
Class 1											1
Class 2											1
Class 3											2
Class 4											2
Class 5											2
Class 6											2

Options	1	2	3	4	5	Demand
Class 1	yes		yes	yes		1
Class 2				yes		1
Class 3		yes			yes	2
Class 4		yes		yes		2
Class 5	yes		yes			2
Class 6	yes	yes				2
Capacity	1/2	2/3	1/3	2/5	1/5	

Setup	1	2	3	4	5	6	7	8	9	10	Capacity
Option 1											1/2
Option 2											2/3
Option 3											1/3
Option 4											2/5
Option 5											1/5

0
1
1
0
1

Swaps

Swaps

- ▶ Neighborhood
 - swap two configurations on the assembly line

Swaps

- ▶ Neighborhood
 - swap two configurations on the assembly line
- ▶ Why swaps, not assignments
 - automatically maintain the demand constraint, that is the correct number of configurations is indeed produced
 - hard constraints
 - always feasible during the search
 - soft constraints
 - may be violated during the search

The Magic Square Problem

```
range R = 1..n;  
range D = 1..n^2;  
int T = n*(n^2+1)/2;  
var{int} s[R,R] in D;  
solve {  
    forall(i in R) {  
        sum(j in R) s[i,j] = T;  
        sum(j in R) s[j,i] = T;  
    }  
    sum(i in R) s[i,i] = T;  
    sum(i in R) s[i,n-i+1] = T;  
    alldifferent(all(i in R,j in R) s[i,j]);  
}
```

The Magic Square Problem

2	8	7
9	5	3
6	1	4

The Magic Square Problem

2	8	7
9	5	3
6	1	4

The Magic Square Problem

Magic Number: 15

2	8	7
9	5	3
6	1	4

The Magic Square Problem

Magic Number: 15

17

2	8	7
9	5	3
6	1	4

The Magic Square Problem

Magic Number: 15

1

17

2	8	7
9	5	3
6	1	4

The Magic Square Problem

Magic Number: 15

	1	1
17		14
2	8	7
9	5	3
6	1	4

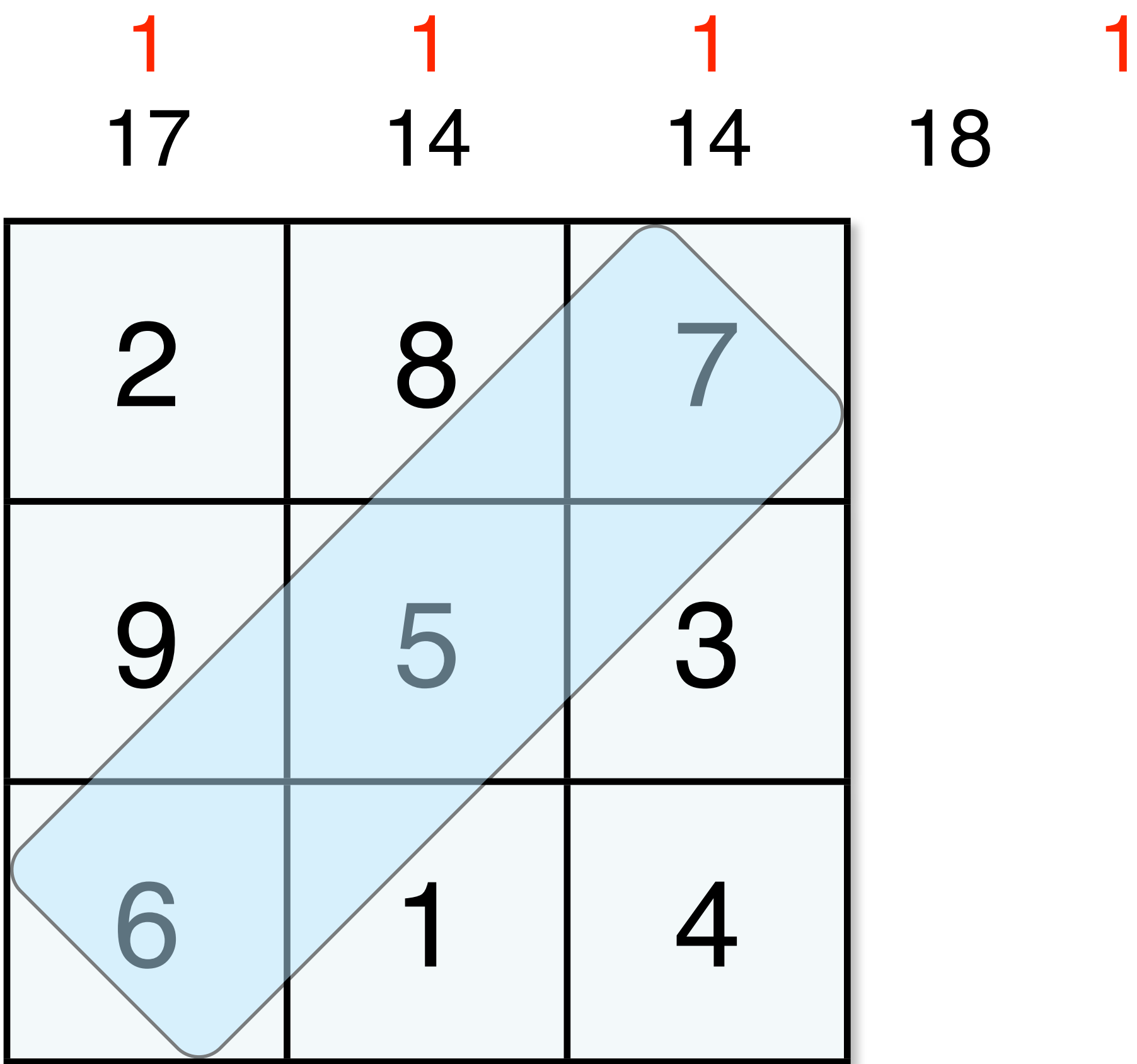
The Magic Square Problem

Magic Number: 15

1	1	1
17	14	14
2	8	7
9	5	3
6	1	4

The Magic Square Problem

Magic Number: 15



The Magic Square Problem

Magic Number: 15

1	1	1	1
17	14	14	18
2	8	7	17
9	5	3	1
6	1	4	

The Magic Square Problem

Magic Number: 15

1	1	1	1
17	14	14	18
2	8	7	17
9	5	3	17
6	1	4	

The Magic Square Problem

Magic Number: 15

1	1	1	1
17	14	14	18
2	8	7	17
9	5	3	17
6	1	4	11

The Magic Square Problem

Magic Number: 15

1	1	1	1
17	14	14	18
2	8	7	17
9	5	3	17
6	1	4	11
			11

The Magic Square Problem

Magic Number: 15

1	1	1	1
17	14	14	18
2	8	7	17
9	5	3	17
6	1	4	11
			11

The Magic Square Problem

Magic Number: 15

1	1	1	1
17	14	14	18
2	8	7	17
9	5	3	17
6	1	4	11
			11

The Magic Square Problem

Magic Number: 15

17	9	19	18
2	3	7	12
9	5	8	22
6	1	4	11
			11

The Magic Square Problem

Magic Number: 15

1	1	1	1
17	9	19	18
2	3	7	12
9	5	8	22
6	1	4	11
			11

Neighborhood for the Magic Square Problem

- ▶ Swapping the value of two cells
 - the alldifferent constraint as a hard constraint
 - swaps are used in many permutation problems
 - the inequalities are the soft constraints

Neighborhood for the Magic Square Problem

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 - the inequalities are the soft constraints
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 - many moves would not change the violations
 - purely random walk

Neighborhood for the Magic Square Problem

- ▶ Swapping the value of two cells
 - the alldifferent constraint as a hard constraint
 - swaps are used in many permutation problems
 - the inequalities are the soft constraints
- ▶ What the violations?
 - 0/1 violations would be pretty useless
 - many moves would not change the violations
 - purely random walk
- ▶ For an equation $l = r$
 - use $\text{abs}(l - r)$ as a measure of violations
 - drives the search much more effectively

The Magic Square Problem

Magic Number: 15

17	14	14	18
2	8	7	17
9	5	3	17
6	1	4	11
			11

The Magic Square Problem

Magic Number: 15

	2			
17		14	14	18
	2	8	7	17
	9	5	3	17
	6	1	4	11
				11

The Magic Square Problem

Magic Number: 15

2	1	1	3
17	14	14	18
2	8	7	17 2
9	5	3	17 3
6	1	4	11 4
			11 4

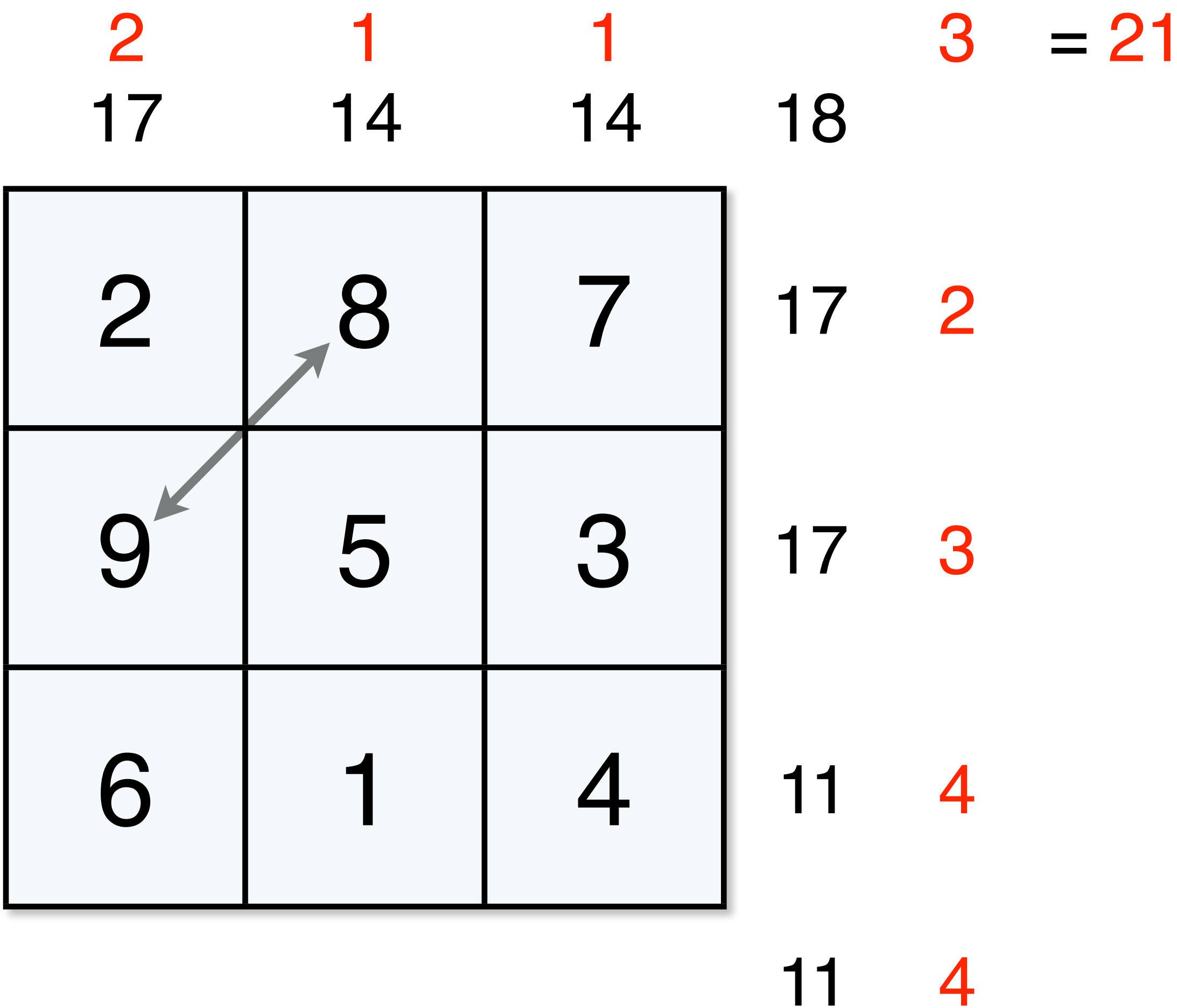
The Magic Square Problem

Magic Number: 15

2	1	1	3	= 21
17	14	14	18	
2	8	7	17	2
9	5	3	17	3
6	1	4	11	4
			11	4

The Magic Square Problem

Magic Number: 15



The Magic Square Problem

Magic Number: 15

16	15	14	18
2	9	7	18
8	5	3	16
6	1	4	11
			11

The Magic Square Problem

Magic Number: 15

1	0	1	3	=	14
16	15	14	18		
2	9	7	18	3	
8	5	3	16	1	
6	1	4	11	4	
			11	4	

The Magic Square Problem

Magic Number: 15

1

16

0

15

1

14

3 = 14

2	9	7	18
8	5	3	16
6	1	4	11

18

3

16

1

11

4

11

4

The Magic Square Problem

Magic Number: 15

16	15	14	15
2	9	4	15
8	5	3	16
6	1	7	14
			14

The Magic Square Problem

Magic Number: 15

1	0	1	0	= 5
16	15	14	15	
2	9	4	15	0
8	5	3	16	1
6	1	7	14	1
			14	1

The Magic Square Problem

Magic Number: 15

1	0	1	0	= 5
16	15	14	15	
2	9	4	15	0
8	5	3	16	1
6	1	7	14	1
			14	1

The Magic Square Problem

Magic Number: 15

15	15	15	15
2	9	4	15
7	5	3	15
6	1	8	15
			15

The Magic Square Problem

Magic Number: 15

0	0	0	0	= 0
15	15	15	15	
2	9	4	15	0
7	5	3	15	0
6	1	8	15	0
			15	0

Until Next Time