python + AI

Introduction to Artificial Intelligence with Python

Optimization

Constraint Satisfaction

Student:

Student:	Taking classes:
1	A B C
2	B D E
3	C E F
4	E F G

Student:

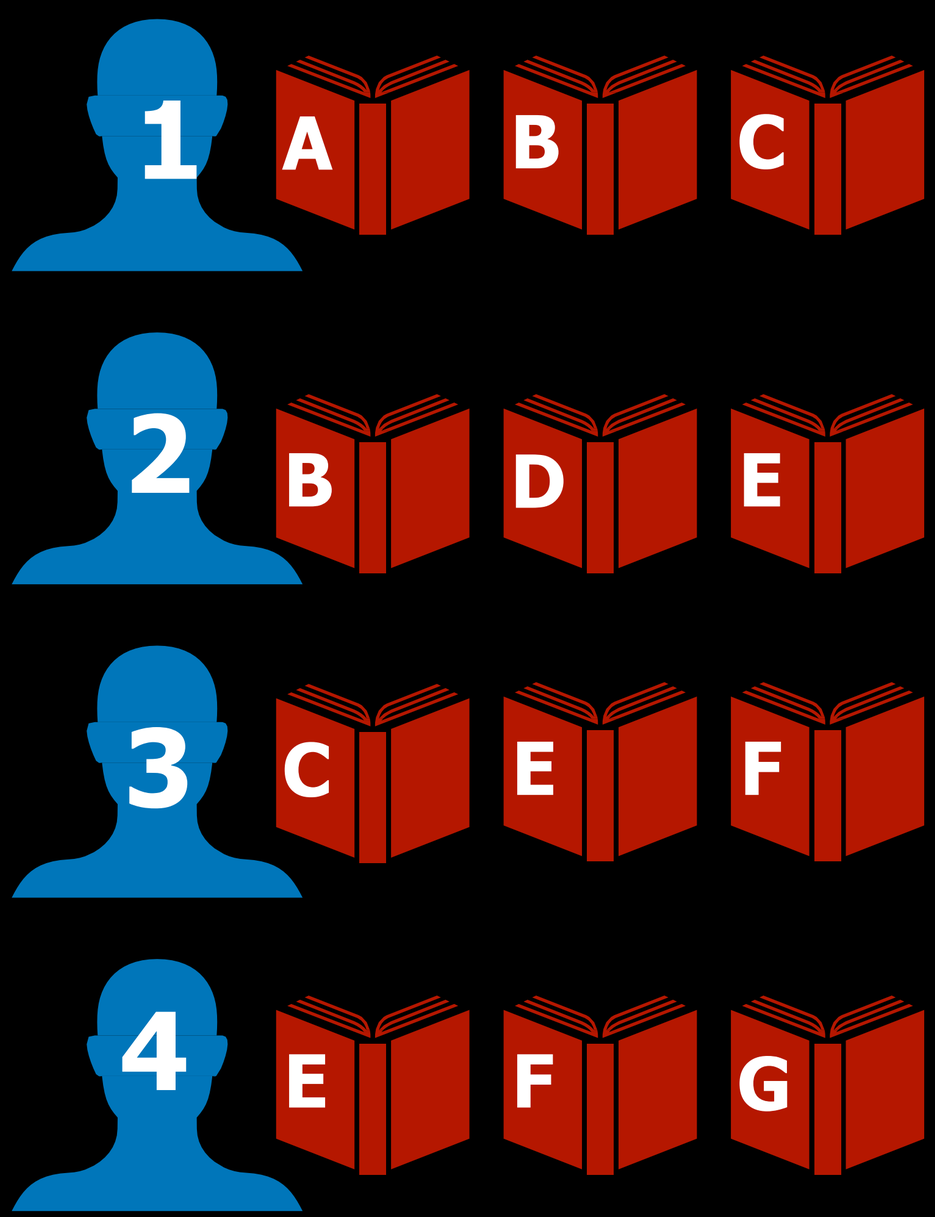
Taking classes:

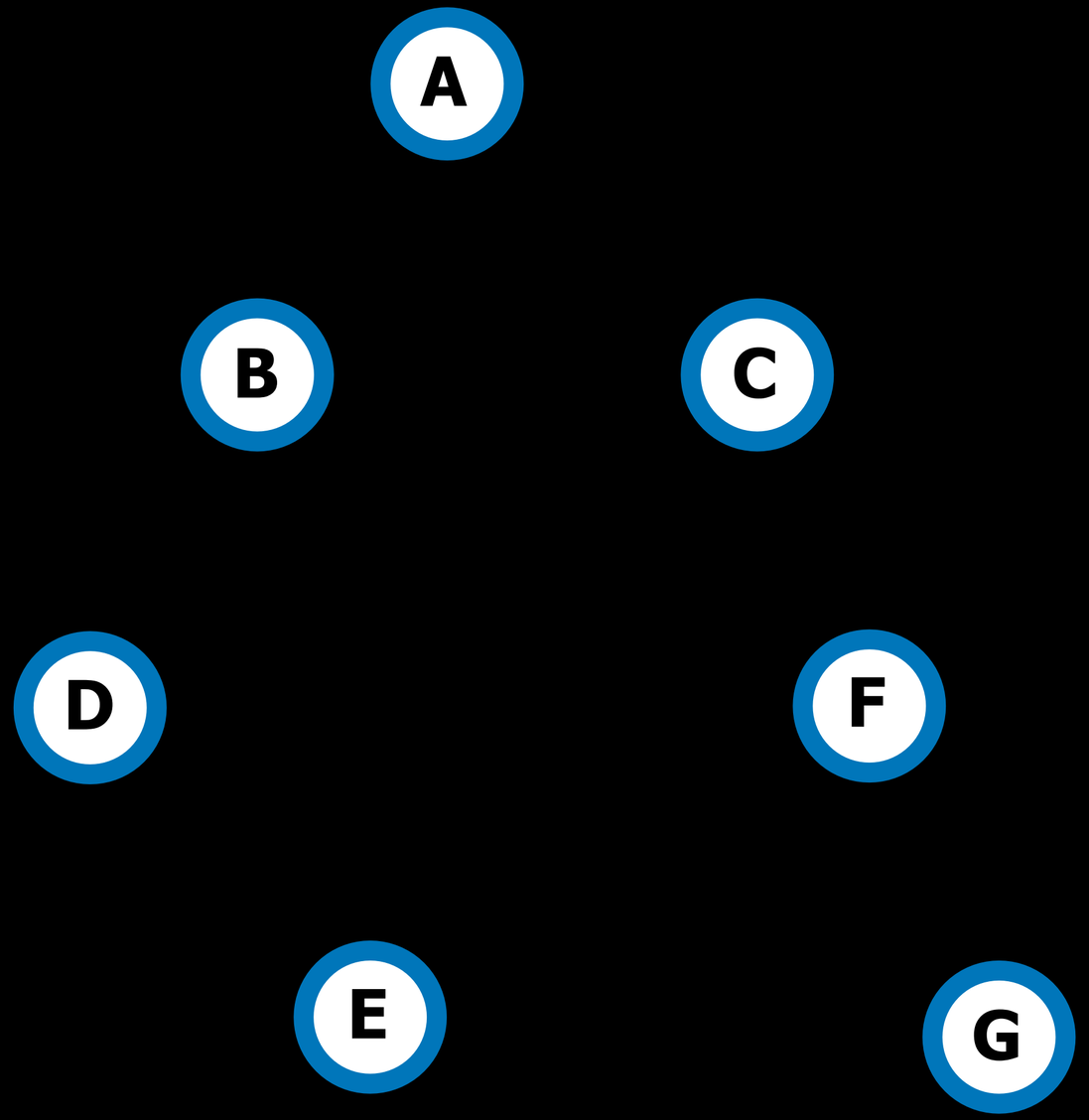
Exam slots:

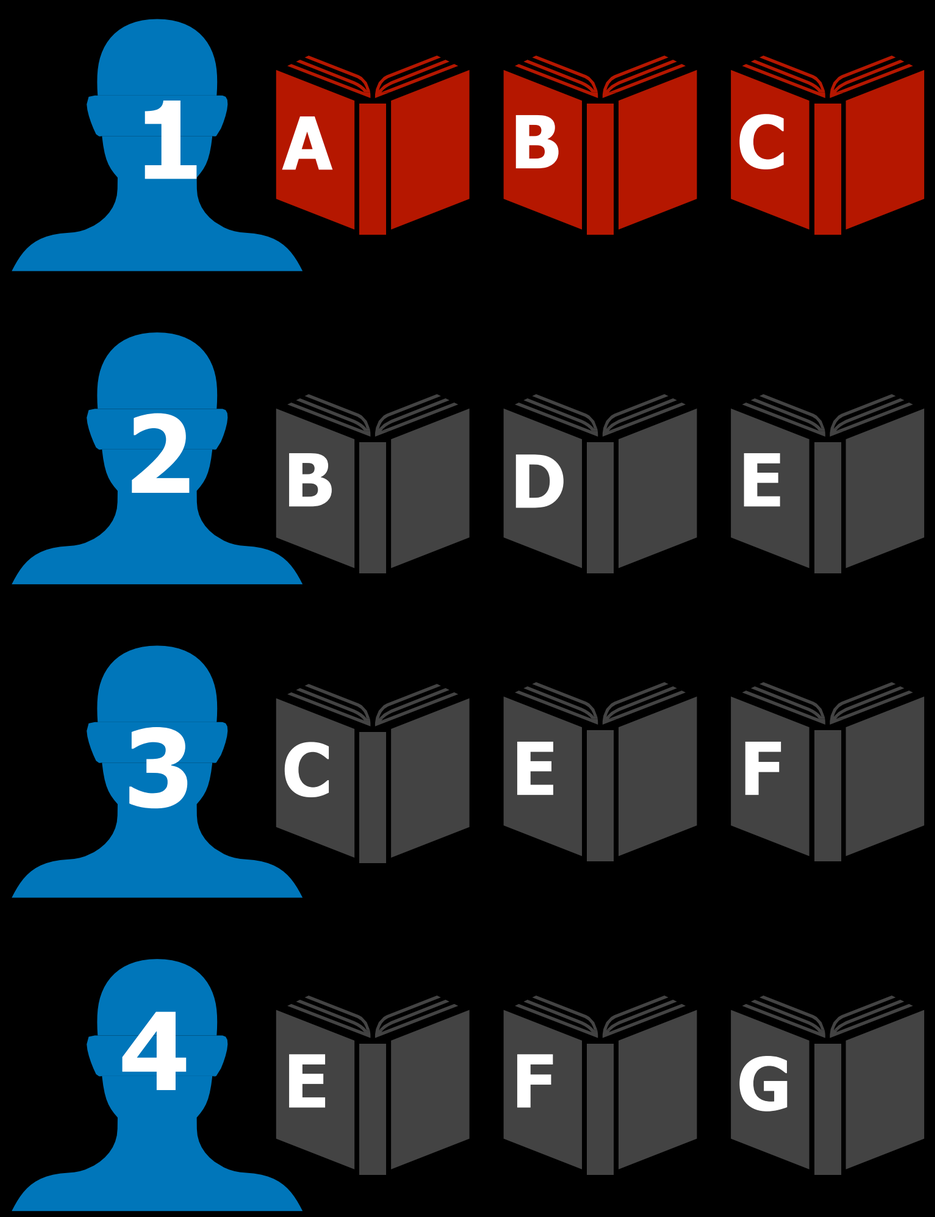
Monday

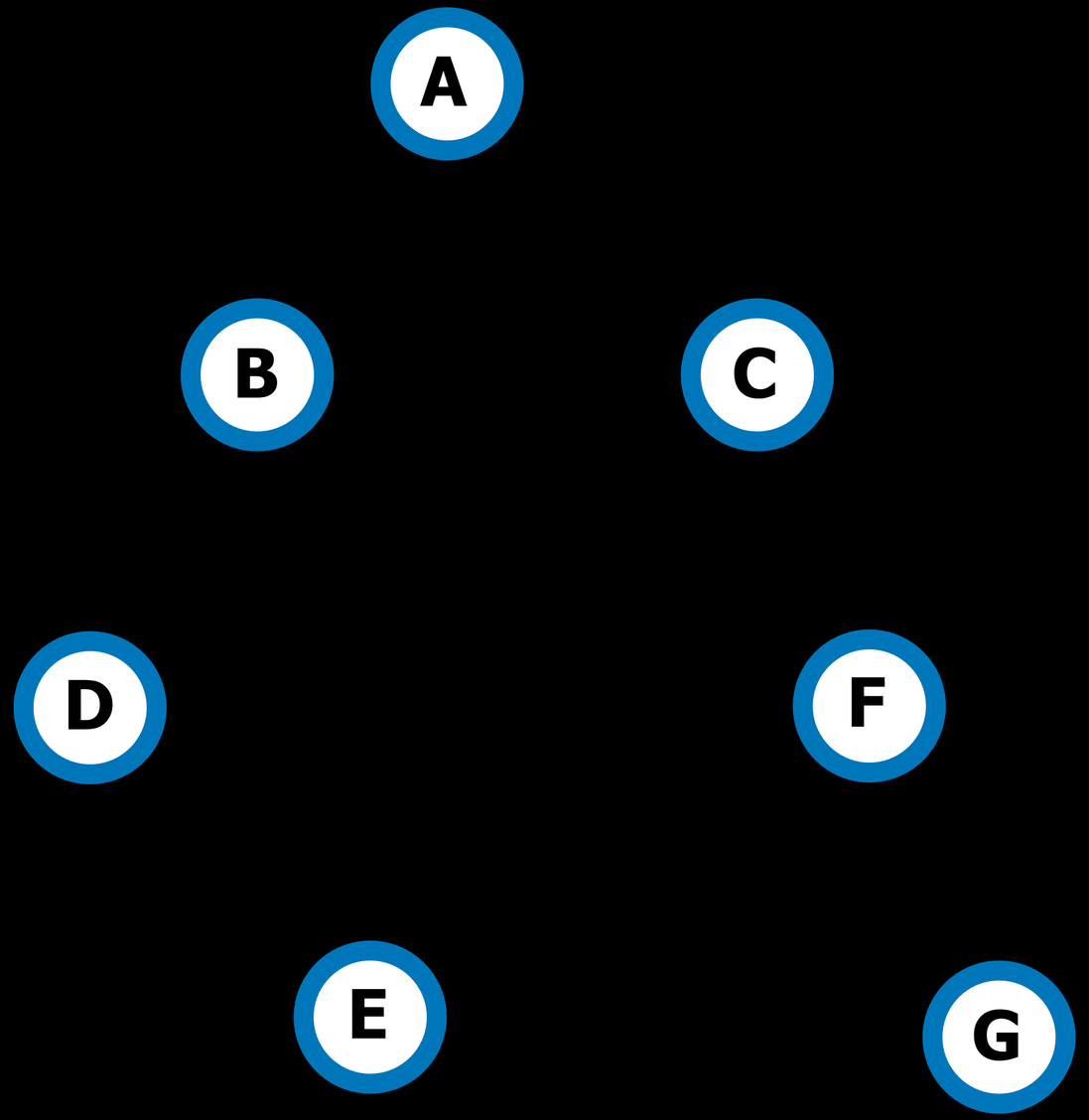
Tuesday

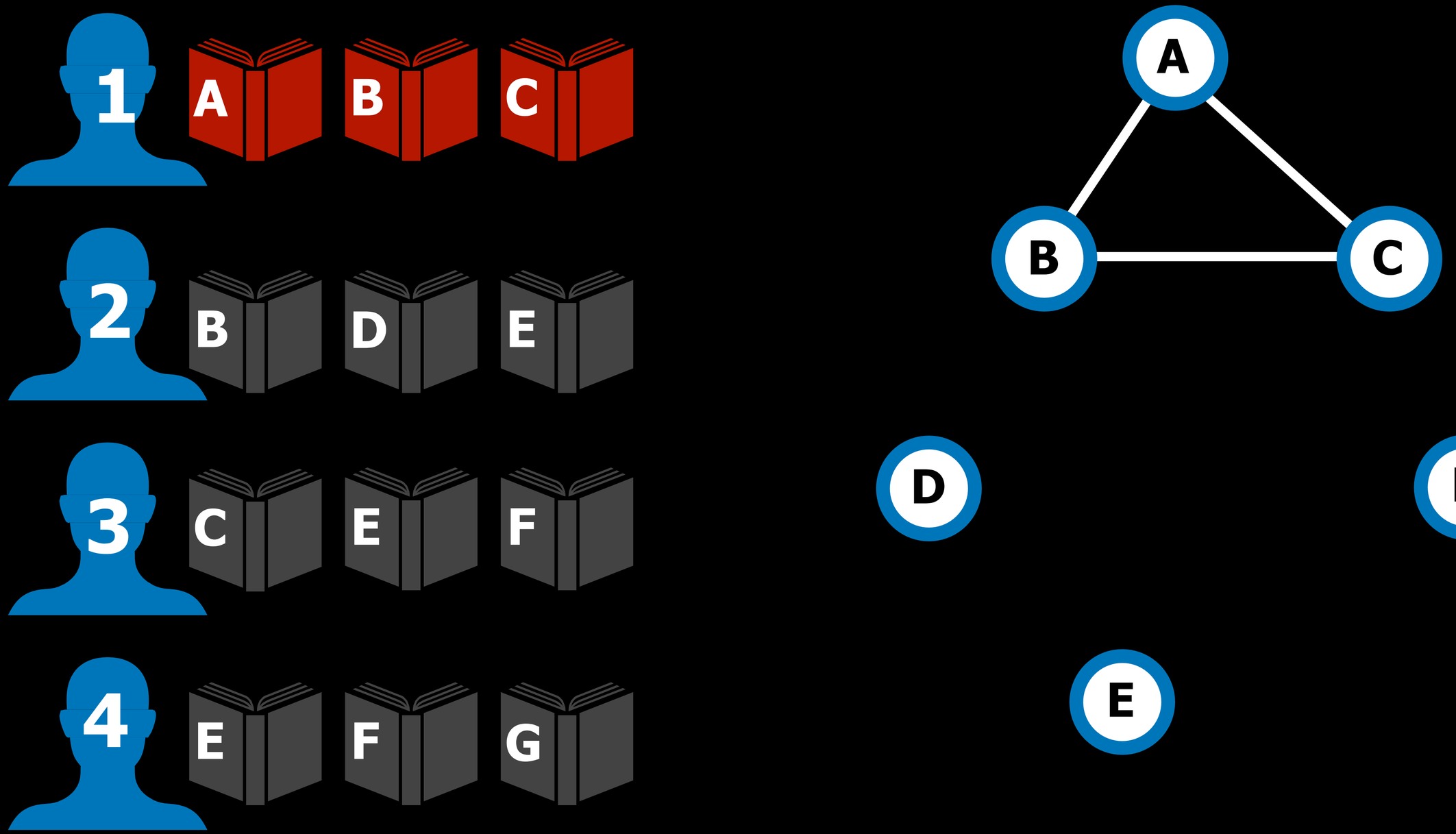
Wednesday

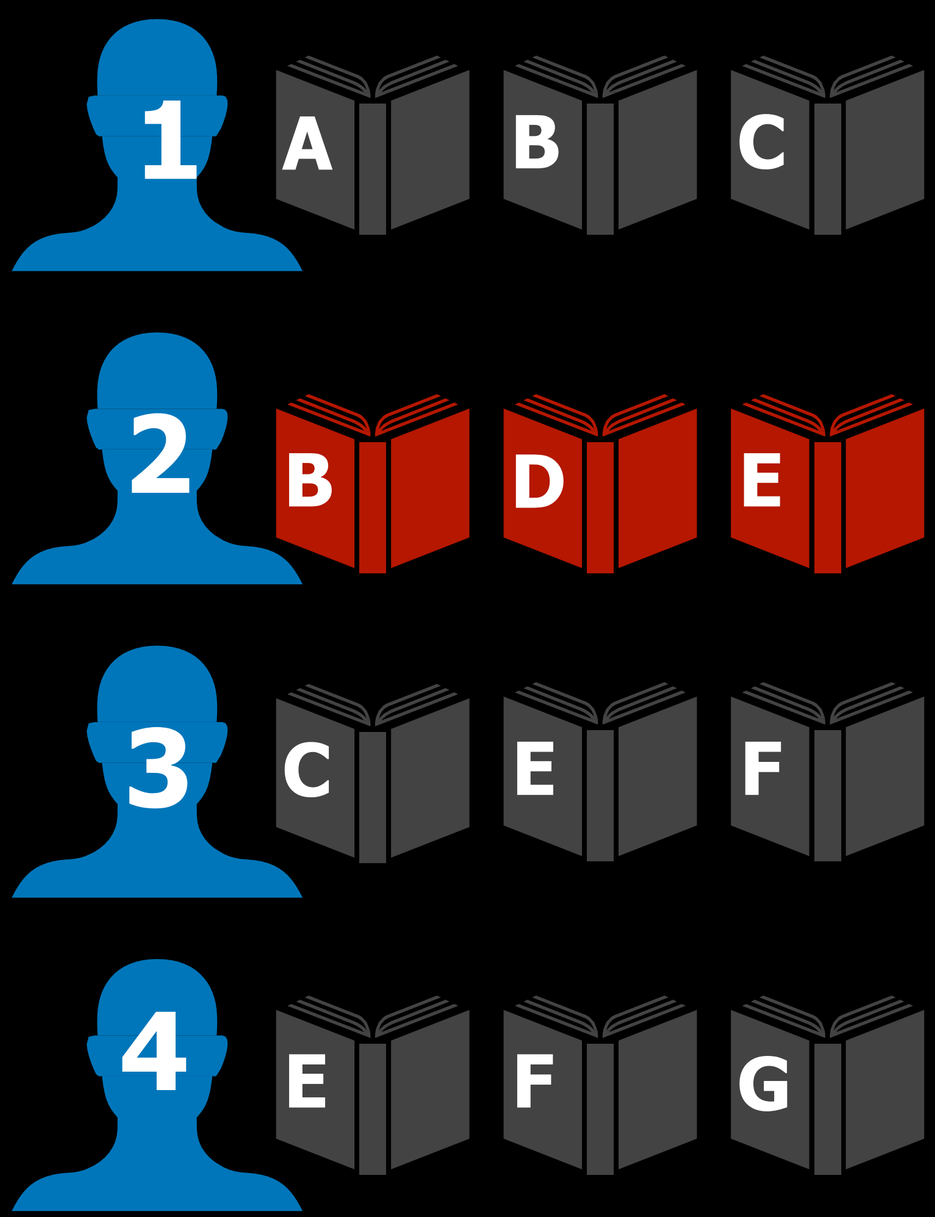

1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G

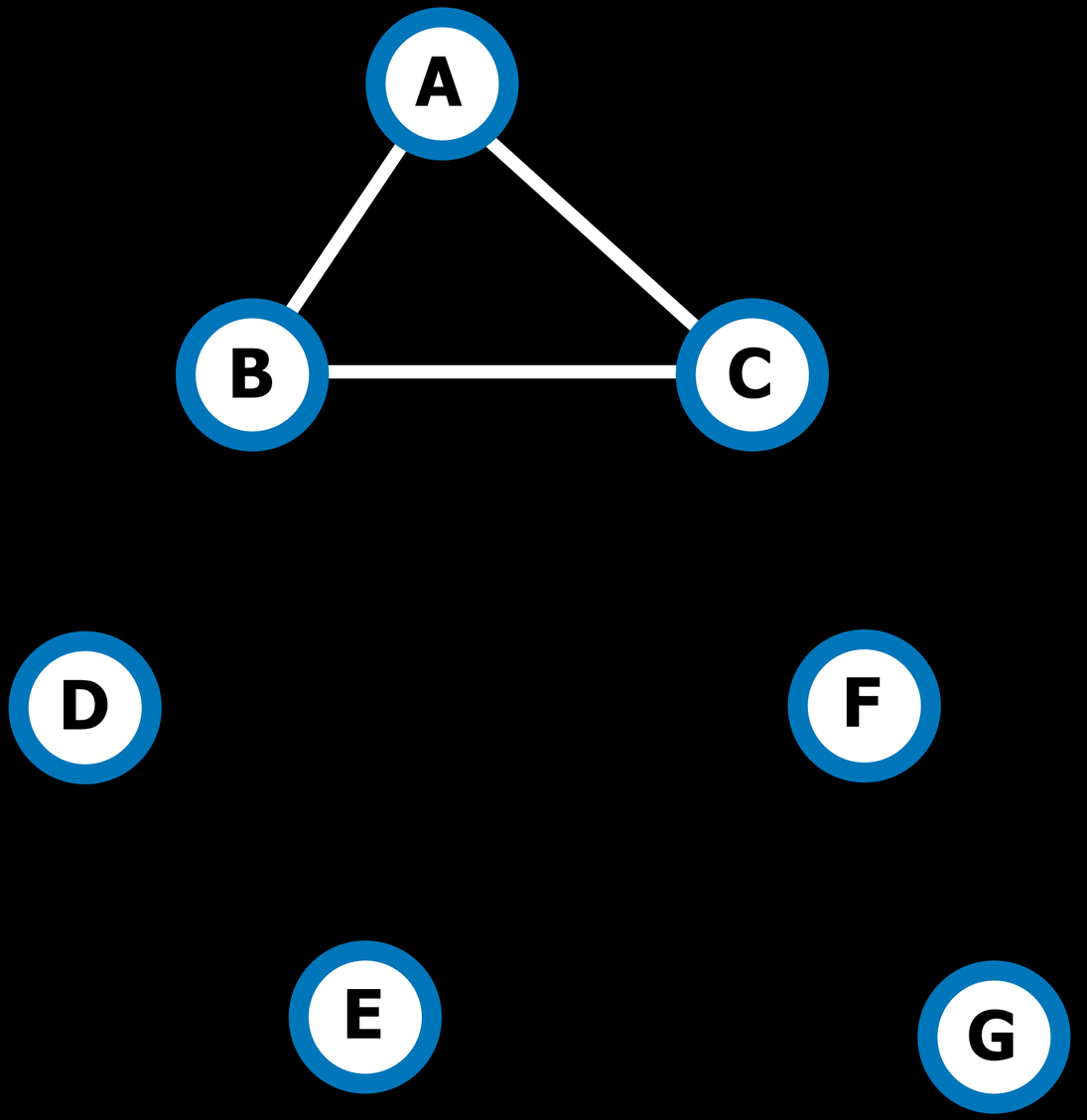

A
B
C
D
F
E
G

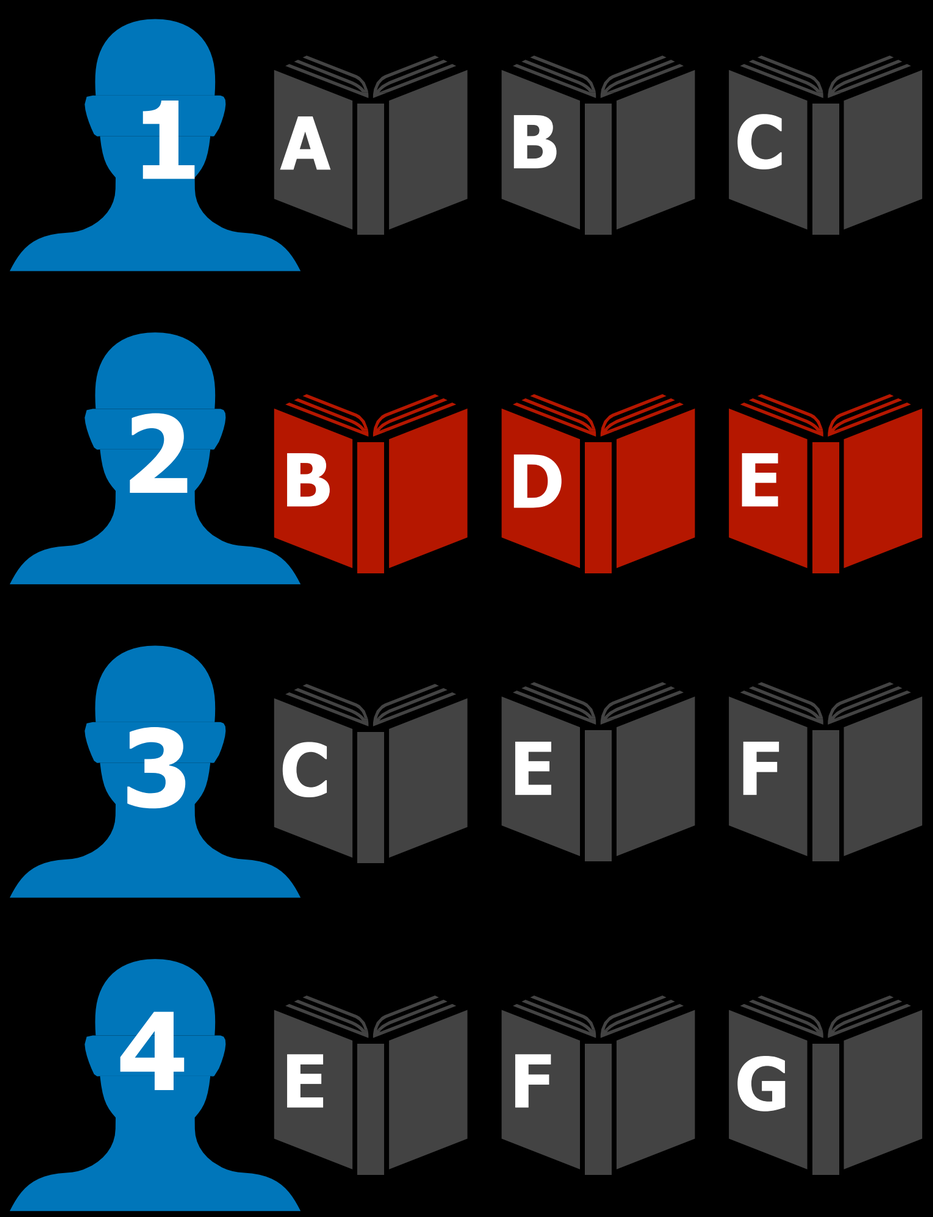

1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G

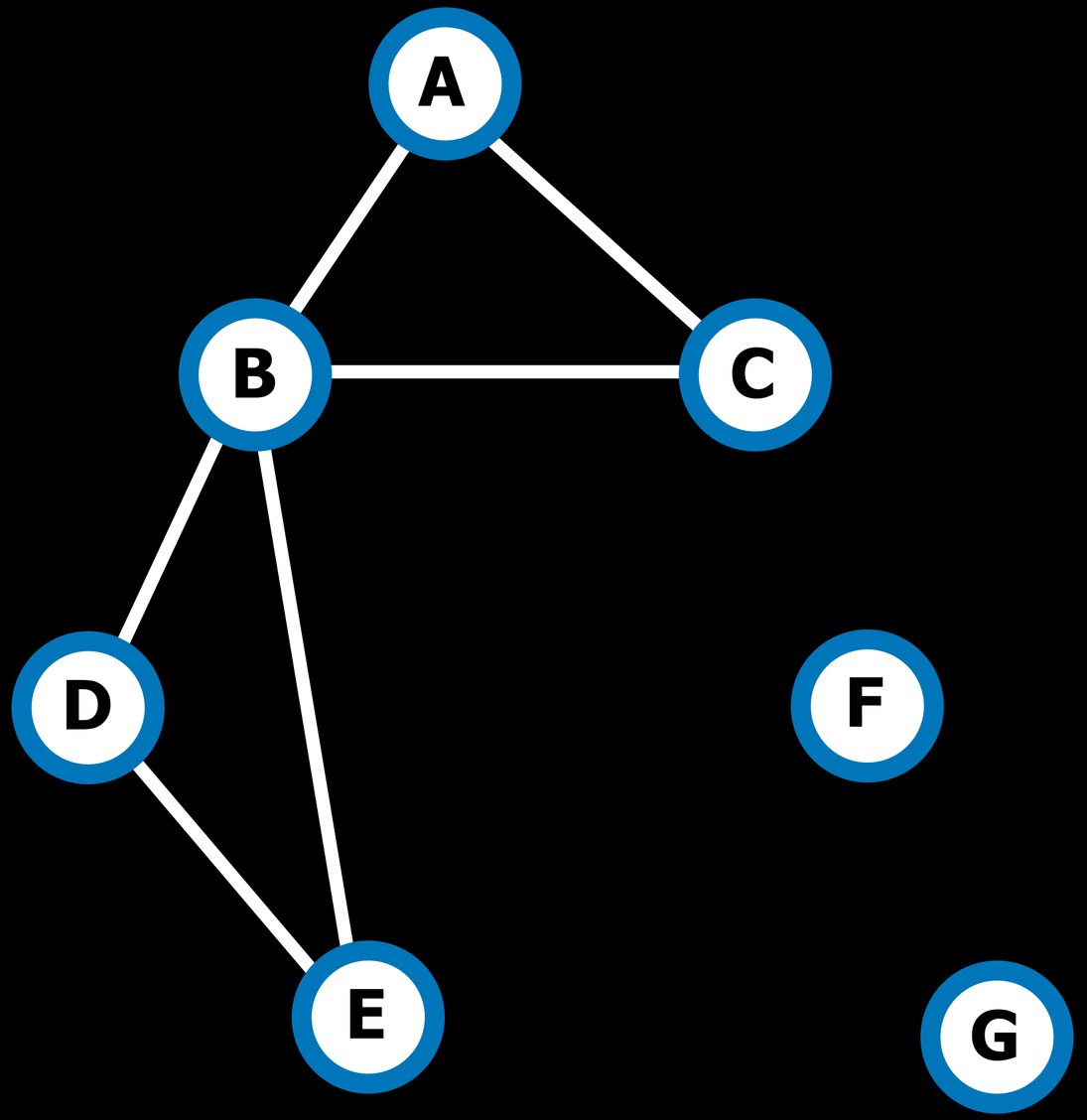

A
B
C
D
F
E
G

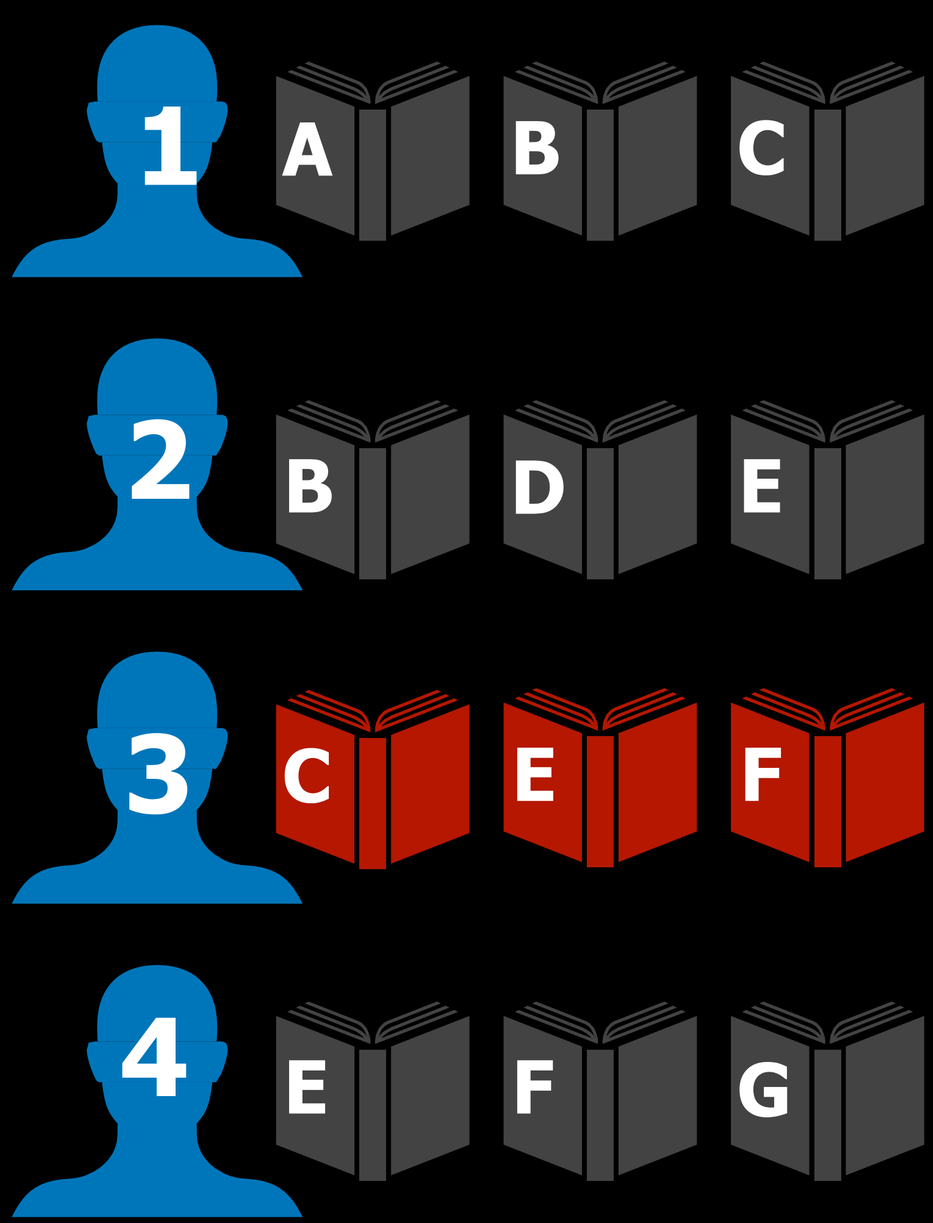

1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G
A
B
C
D
F
E
G

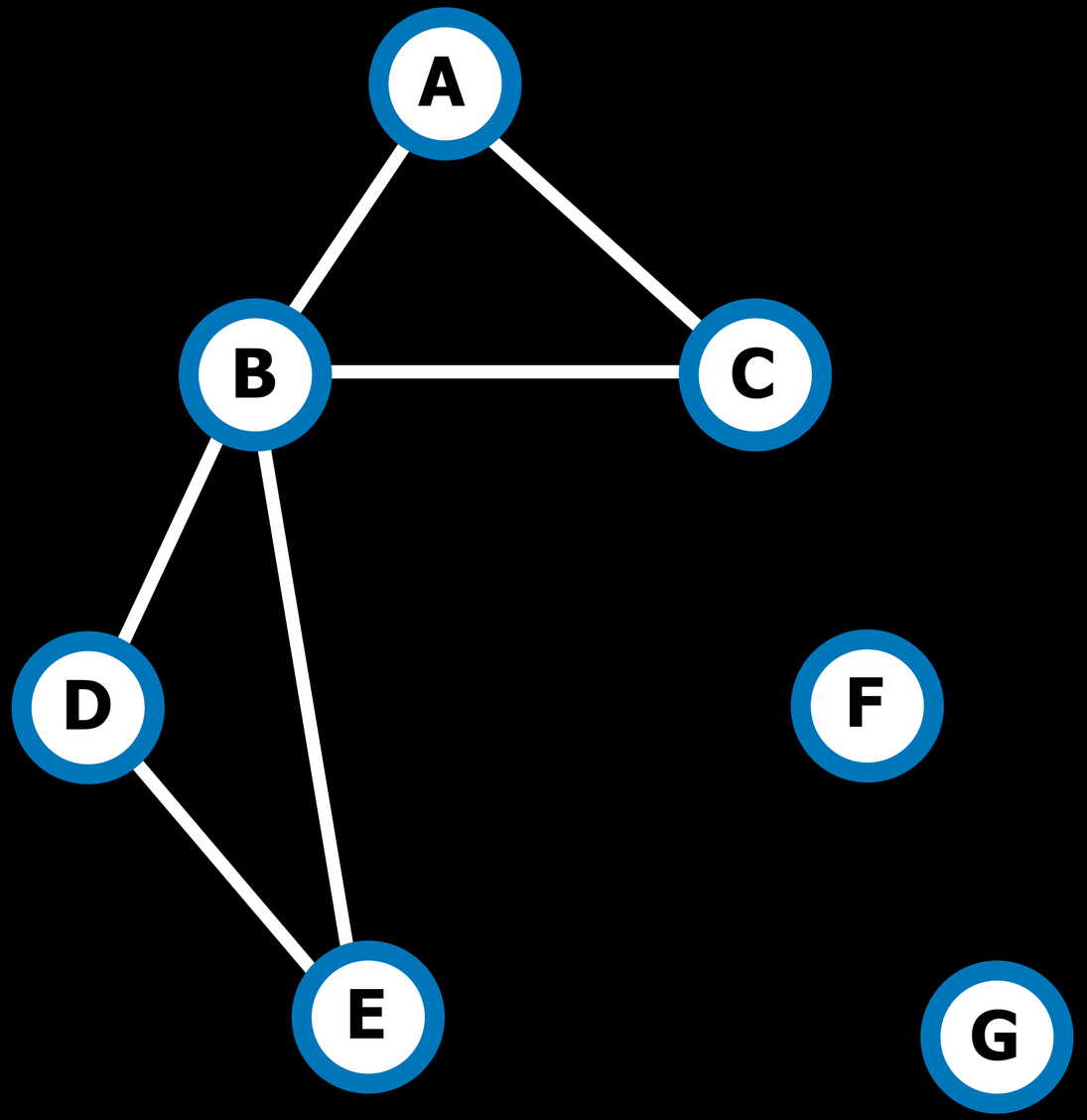

1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G

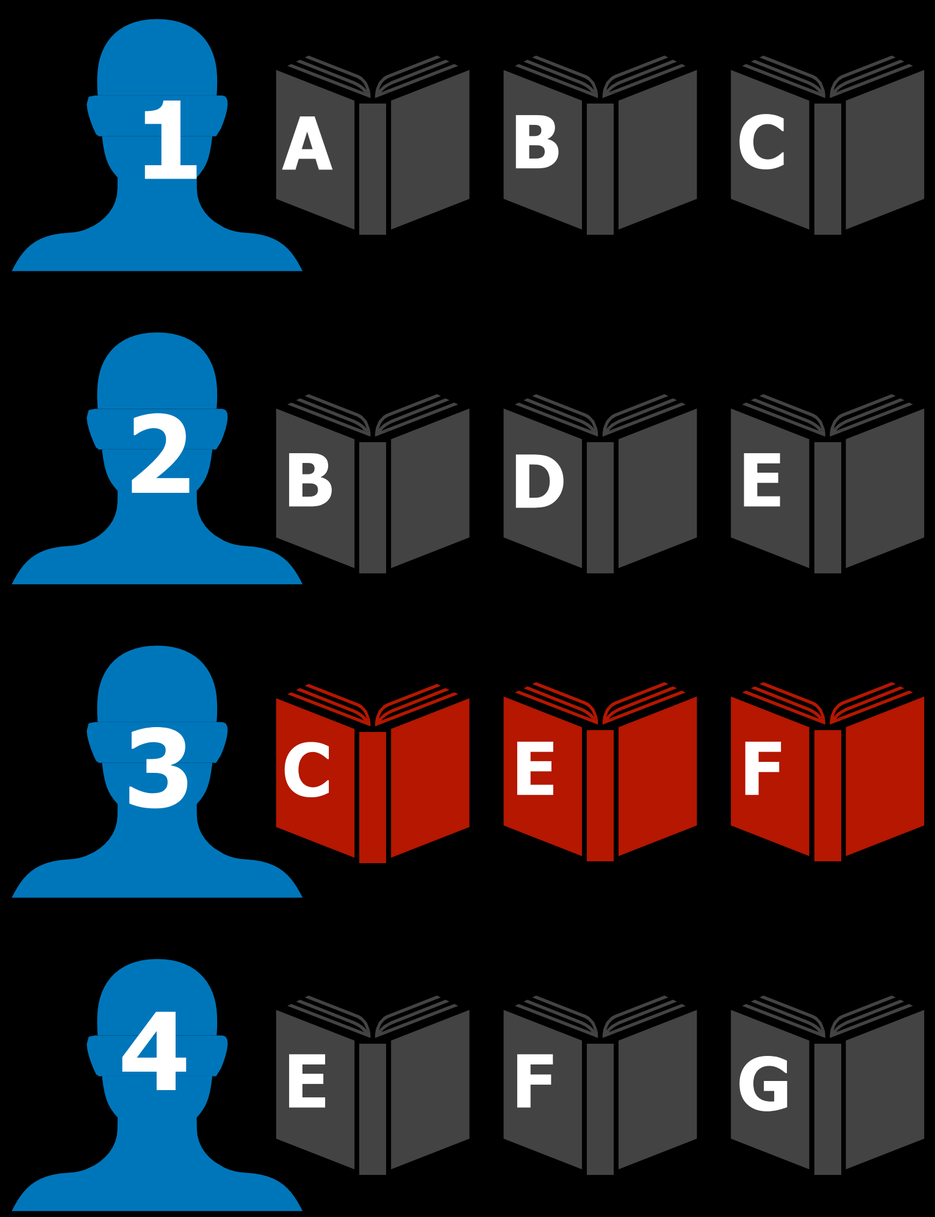

A
B
C
D
F
E
G

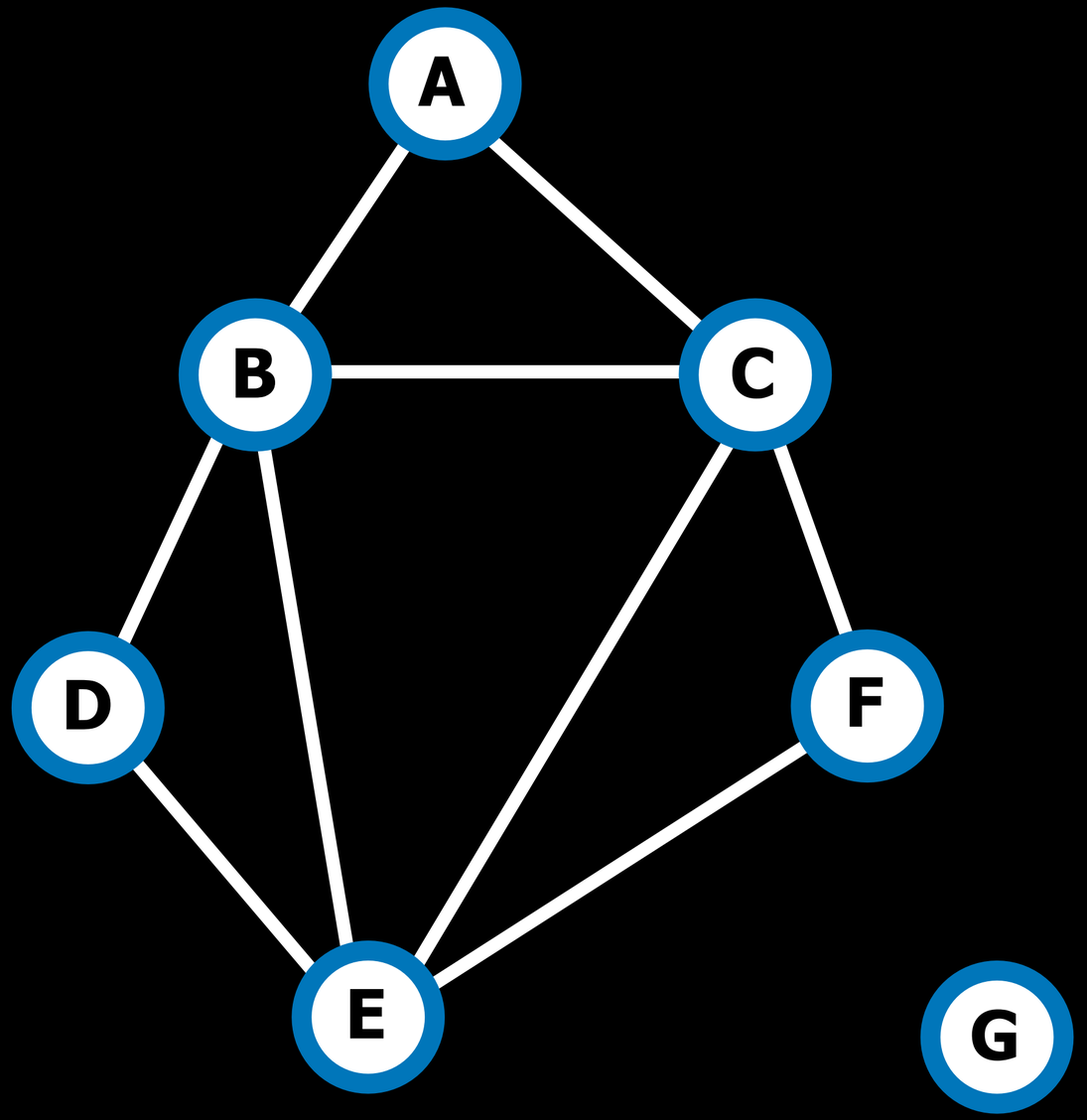

1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G

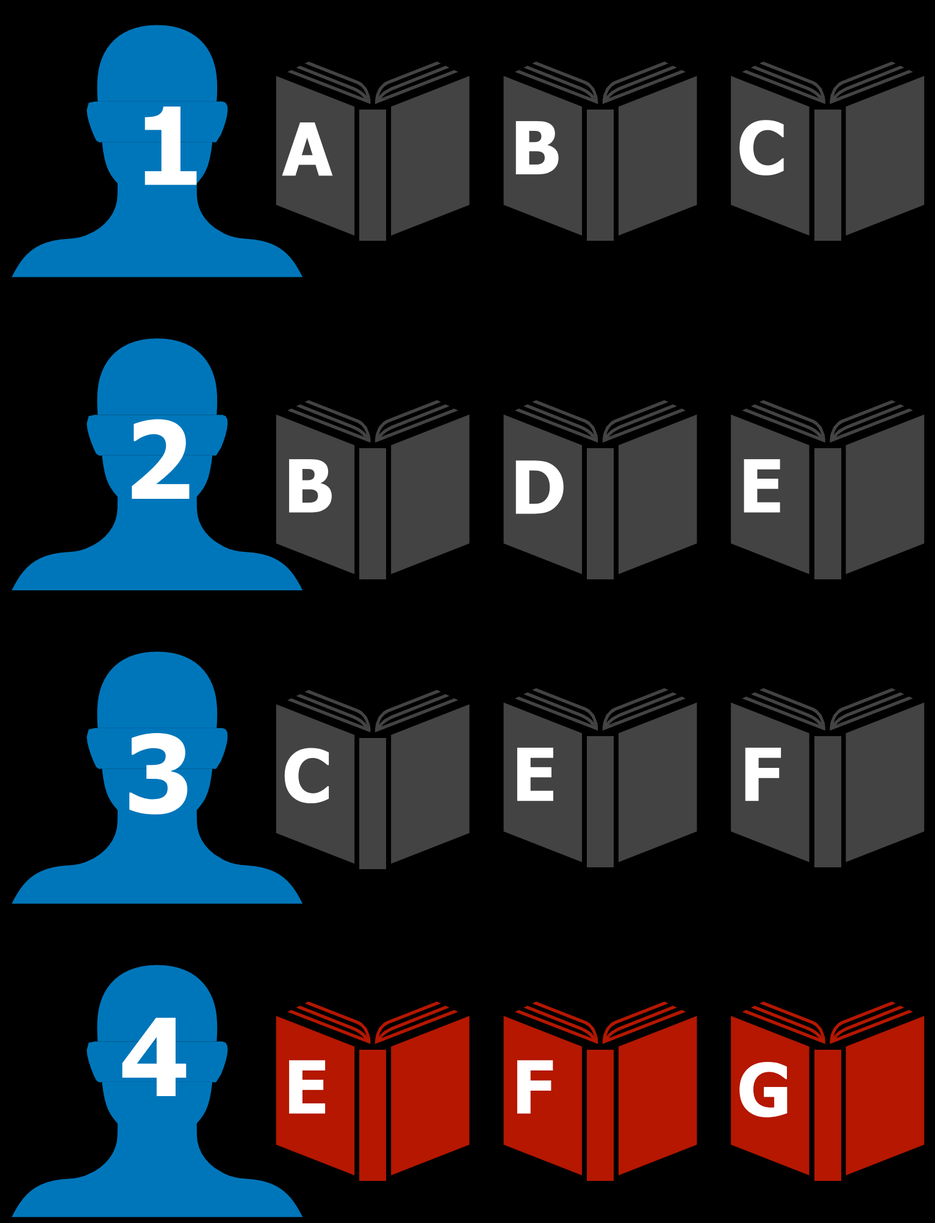

A
B
C
D
F
E
G

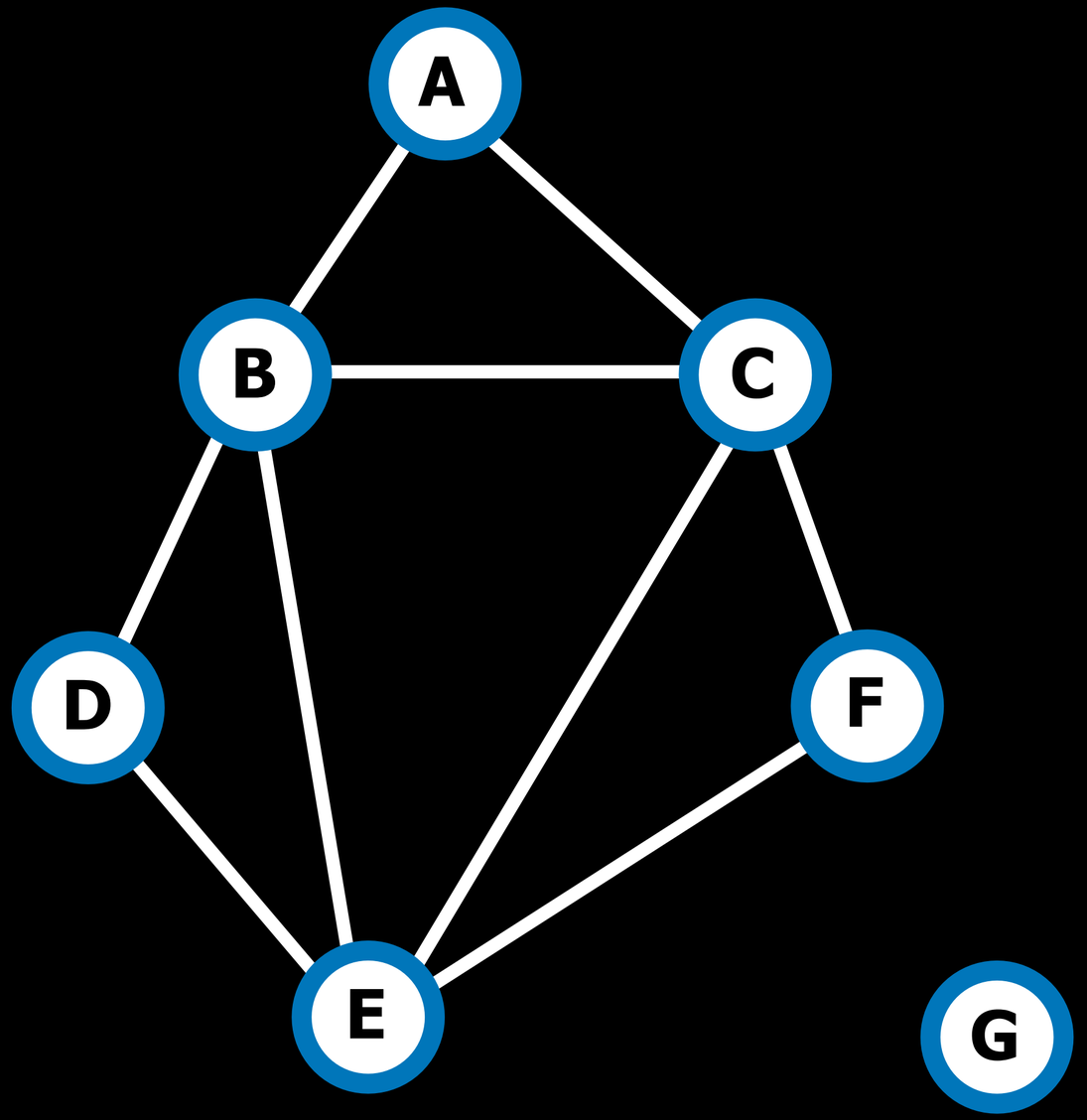

1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G

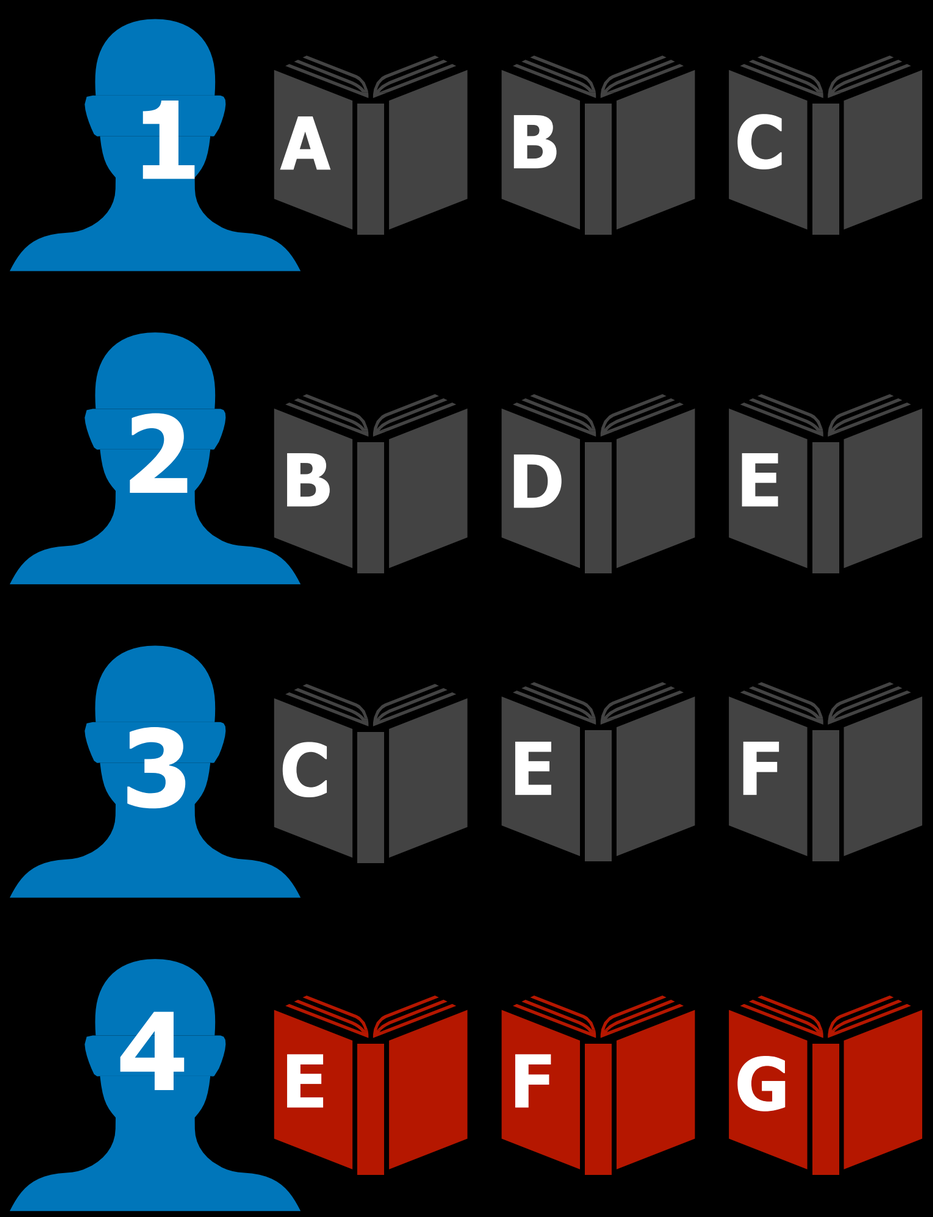

A
B
C
D
F
E
G

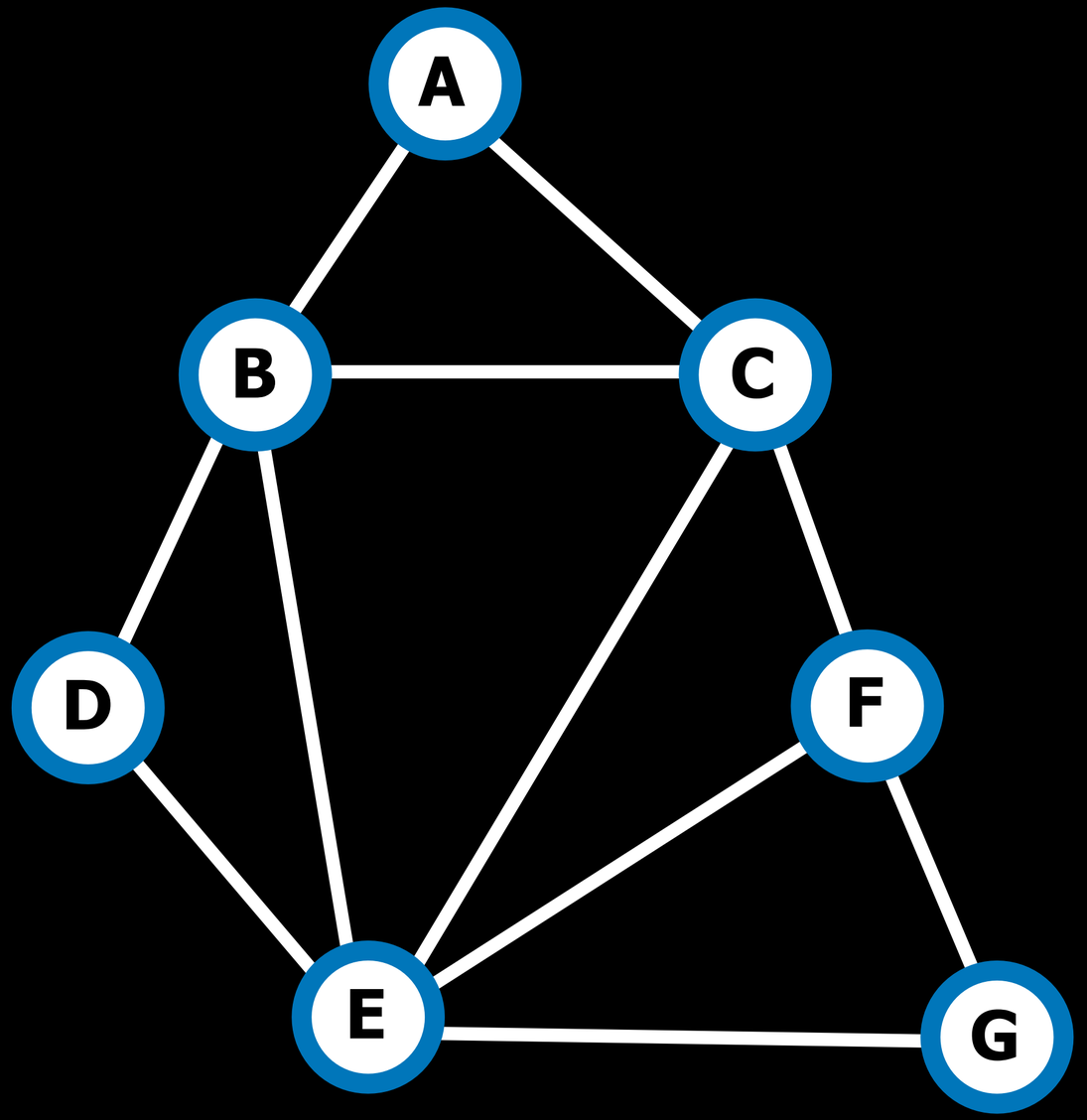

1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G

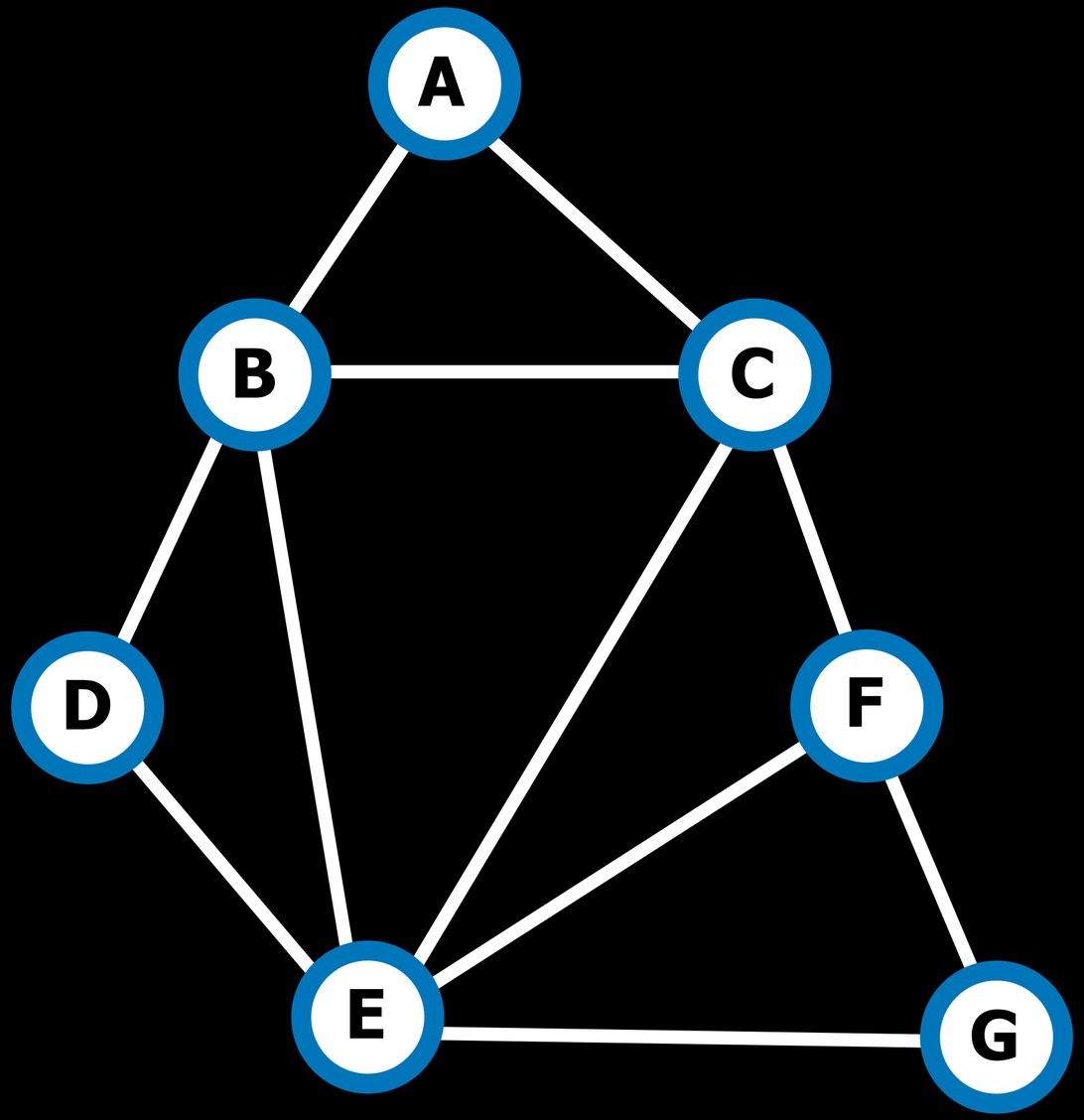

A
B
C
D
F
E
G


1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G


A
B
C
D
F
E
G


1
A
B
C
2
B
D
E
3
C
E
F
4
E
F
G


A
B
C
D
F
E
G


A
B
C
D
F
E
G

Constraint Satisfaction Problem

- Set of variables $\{X_1, X_2, ..., X_n\}$
- Set of domains for each variable $\{D_1, D_2, ..., D_n\}$
- Set of constraints C

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

Variables

$$\{(0, 2), (1, 1), (1, 2), (2, 0), \ldots\}$$

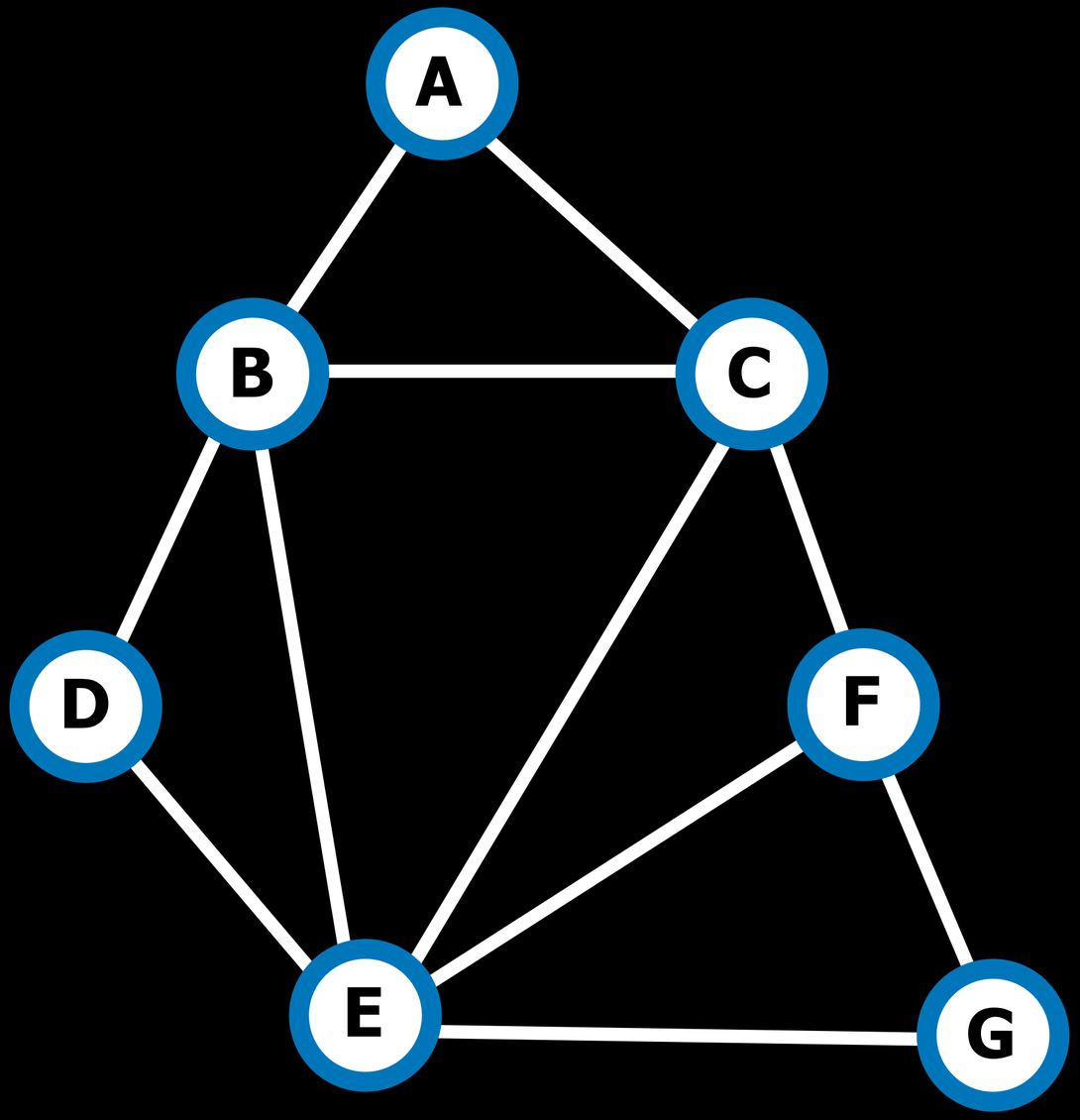
Domains

$$\{1, 2, 3, 4, 5, 6, 7, 8, 9\}$$

for each variable

Constraints

$$\{(0, 2) \neq (1, 1) \neq (1, 2) \neq (2, 0), \ldots\}$$



Variables

$\{A, B, C, D, E, F, G\}$

Domains

$\{Monday, Tuesday, Wednesday\}$

for each variable

Constraints

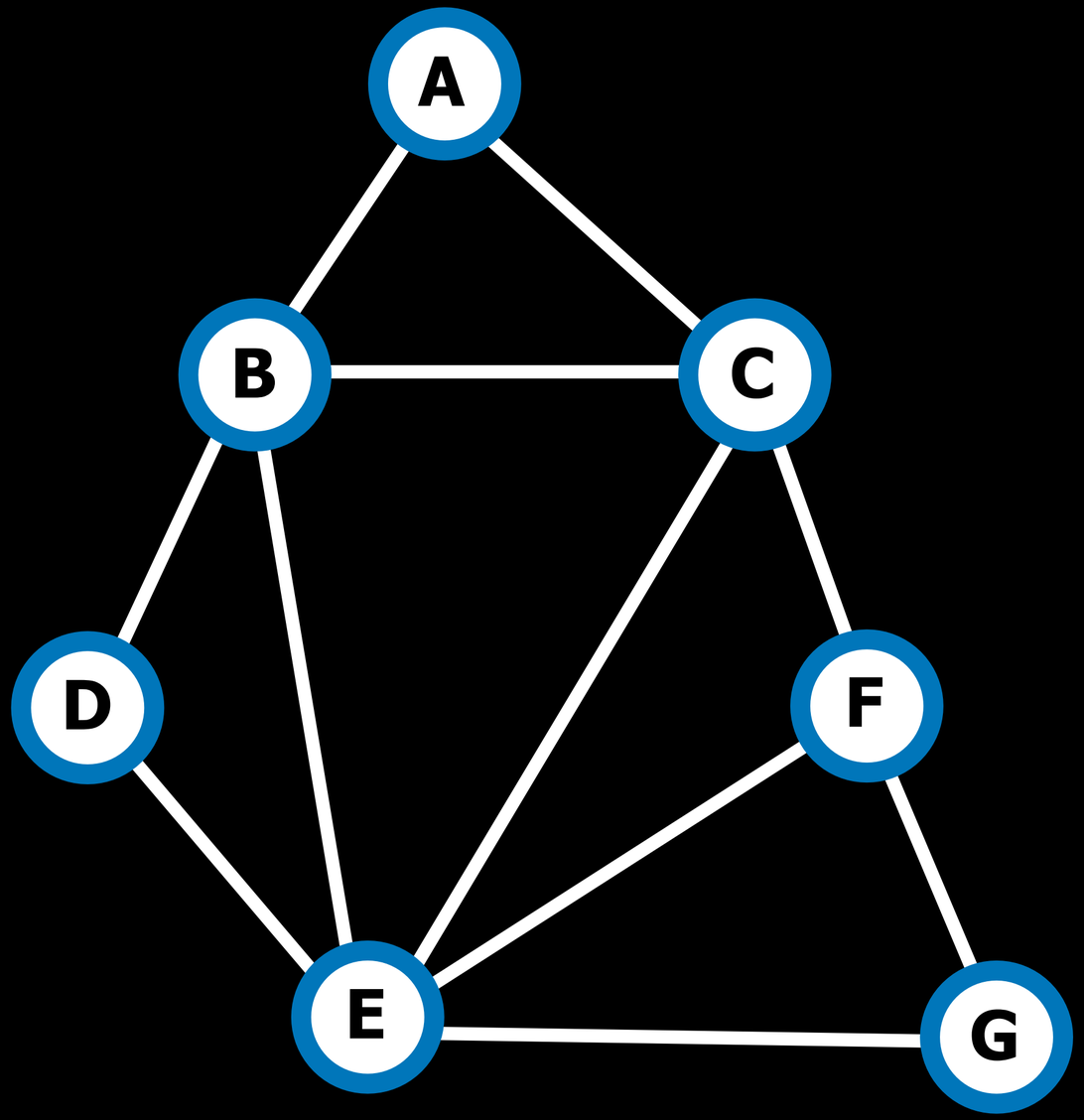
$\{A \neq B, A \neq C, B \neq C, B \neq D, B \neq E, C \neq E, C \neq F, D \neq E, E \neq F, E \neq G, F \neq G\}$

hard constraints

constraints that must be satisfied in a correct solution

soft constraints

constraints that express some notion of which solutions are preferred over others


A
B
C
D
F
E
G

unary constraint

constraint involving only one variable

unary constraint

$\{A \neq Monday\}$

binary constraint

constraint involving two variables

binary constraint

$\{A \neq B\}$

node consistency

when all the values in a variable's domain satisfy the variable's unary constraints

$\{Mon, Tue, Wed\}$ $\{Mon, Tue, Wed\}$

$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$

$\{Mon, Tue, Wed\}$ $\{Mon, Tue, Wed\}$

$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$

$\{Tue, Wed\}$ $\{Mon, Tue, Wed\}$

$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$

$\{Tue, Wed\}$ $\{Mon, Tue, Wed\}$

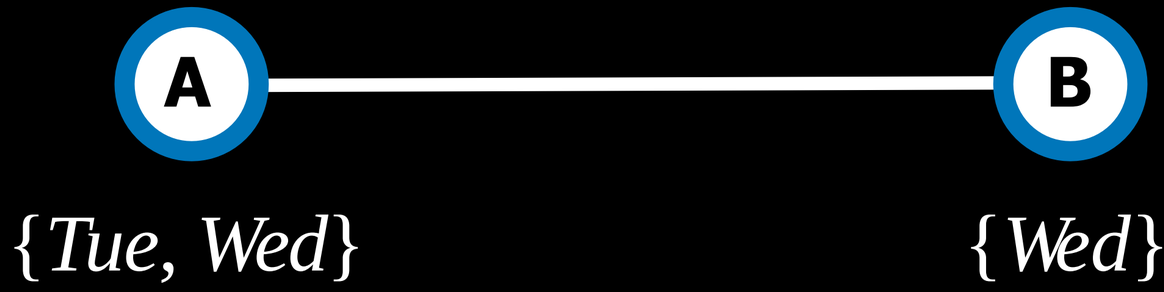
$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$

$\{Tue, Wed\}$ $\{Mon, Wed\}$

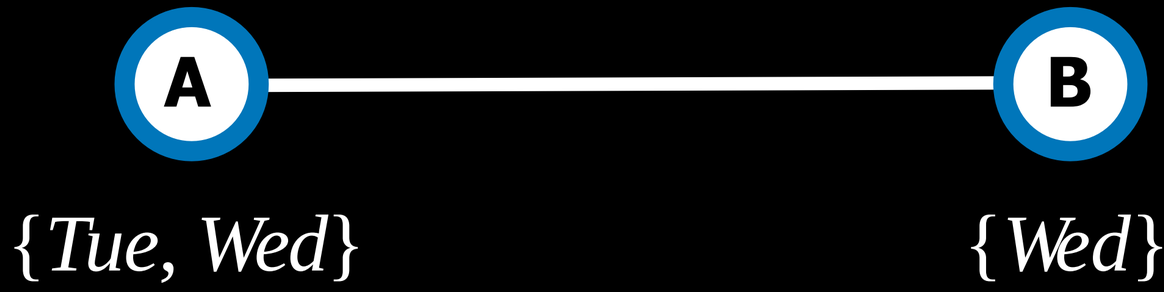
$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$

$\{Tue, Wed\}$ $\{Mon, Wed\}$

$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$



$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$



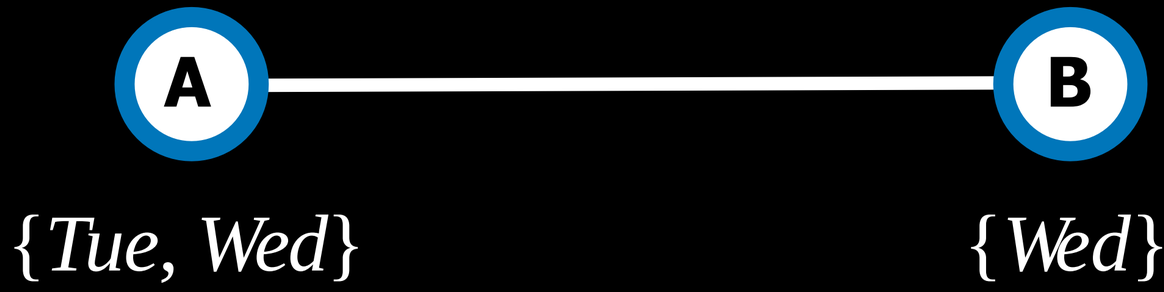
$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$

arc consistency

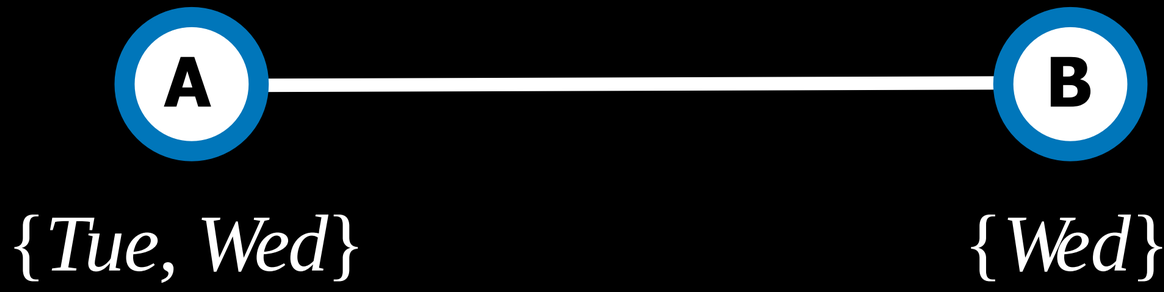
when all the values in a variable's domain satisfy the variable's binary constraints

arc consistency

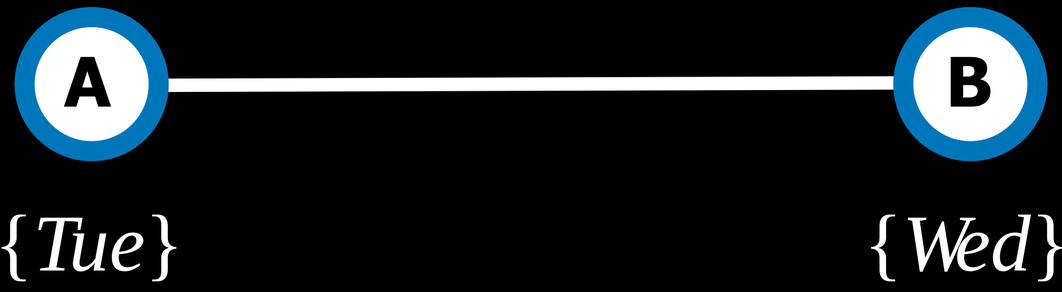
To make X arc-consistent with respect to Y, remove elements from X's domain until every choice for X has a possible choice for Y



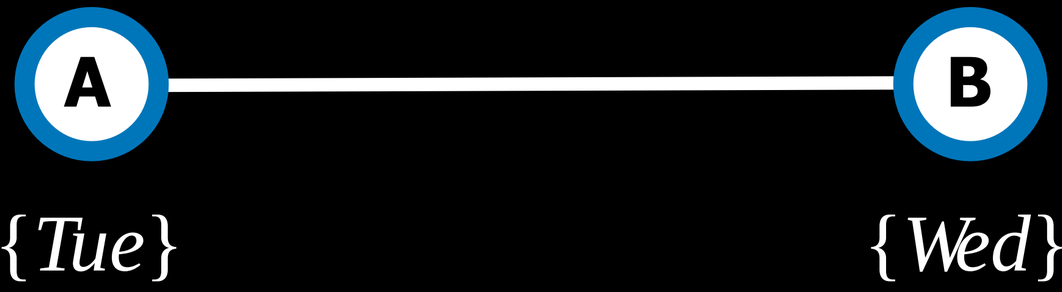
$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$



$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$



$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$



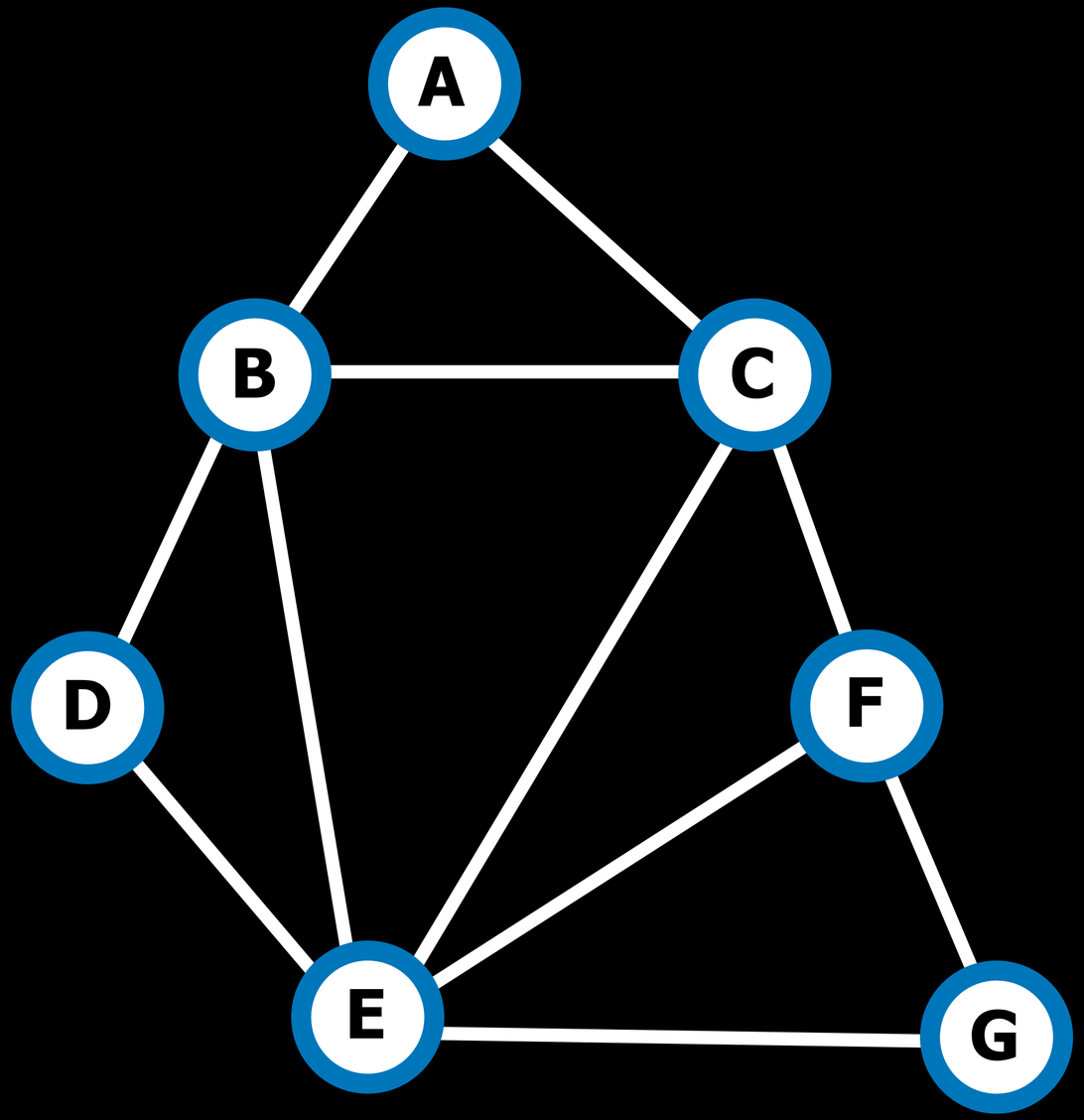
$$\{A \neq Mon, B \neq Tue, B \neq Mon, A \neq B\}$$

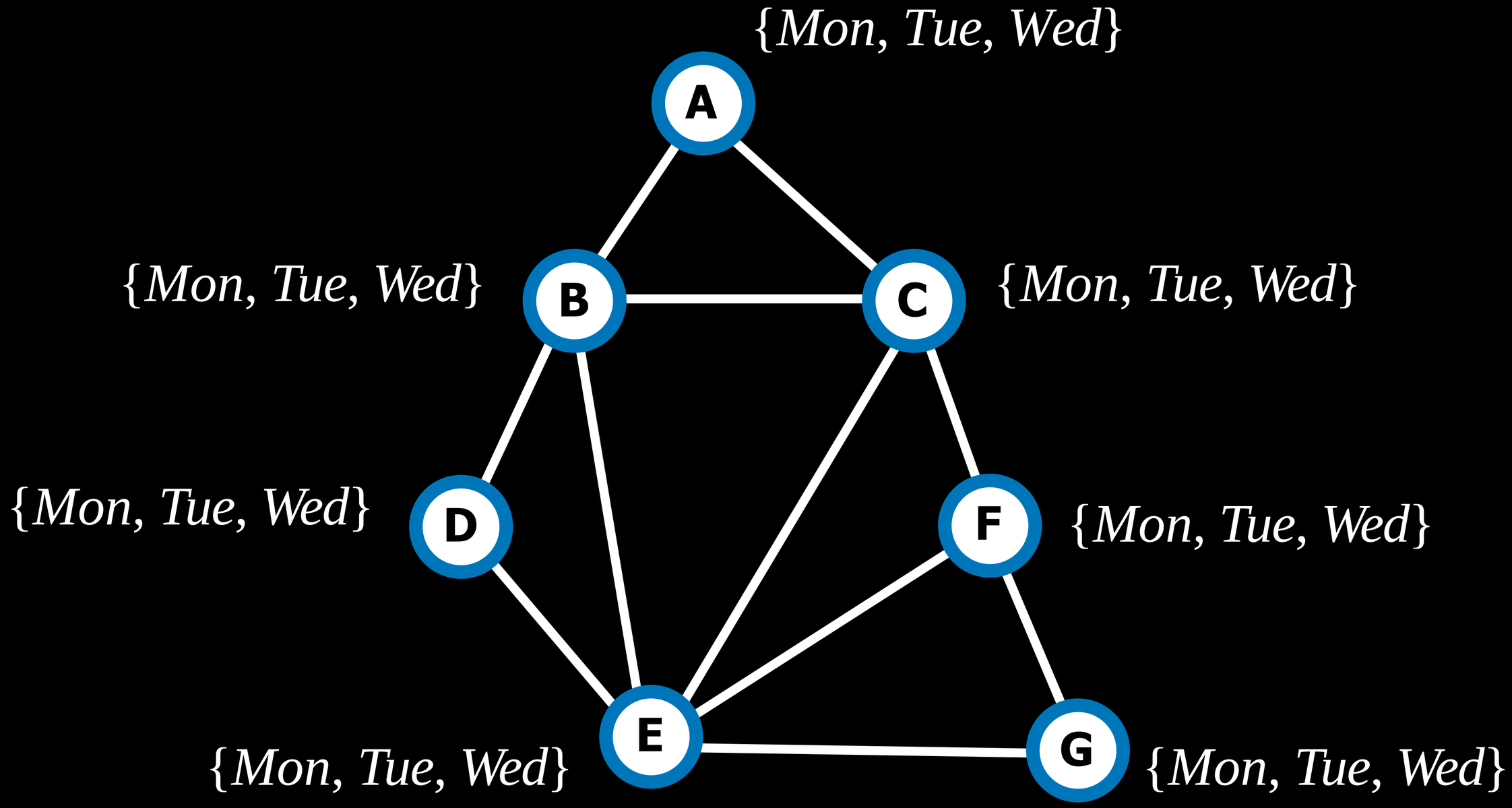
Arc Consistency

```
function REVISE(csp, X, Y):
    revised = false
    for x in X.domain:
        if no y in Y.domain satisfies constraint for (X, Y):
            delete x from X.domain
            revised = true
    return revised
```

Arc Consistency

```
function AC-3(csp):
    queue = all arcs in csp
    while queue non-empty:
        (X, Y) = DEQUEUE(queue)
        if REVISE(csp, X, Y):
            if size of X.domain == 0:
                return false
            for each Z in X.neighbors - {Y}:
                ENQUEUE(queue, (Z, X))
    return true
```


A
B
C
D
F
E
G


{Mon, Tue, Wed}
A
{Mon, Tue, Wed}
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}

Search Problems

- initial state
- actions
- transition model
- goal test
- path cost function

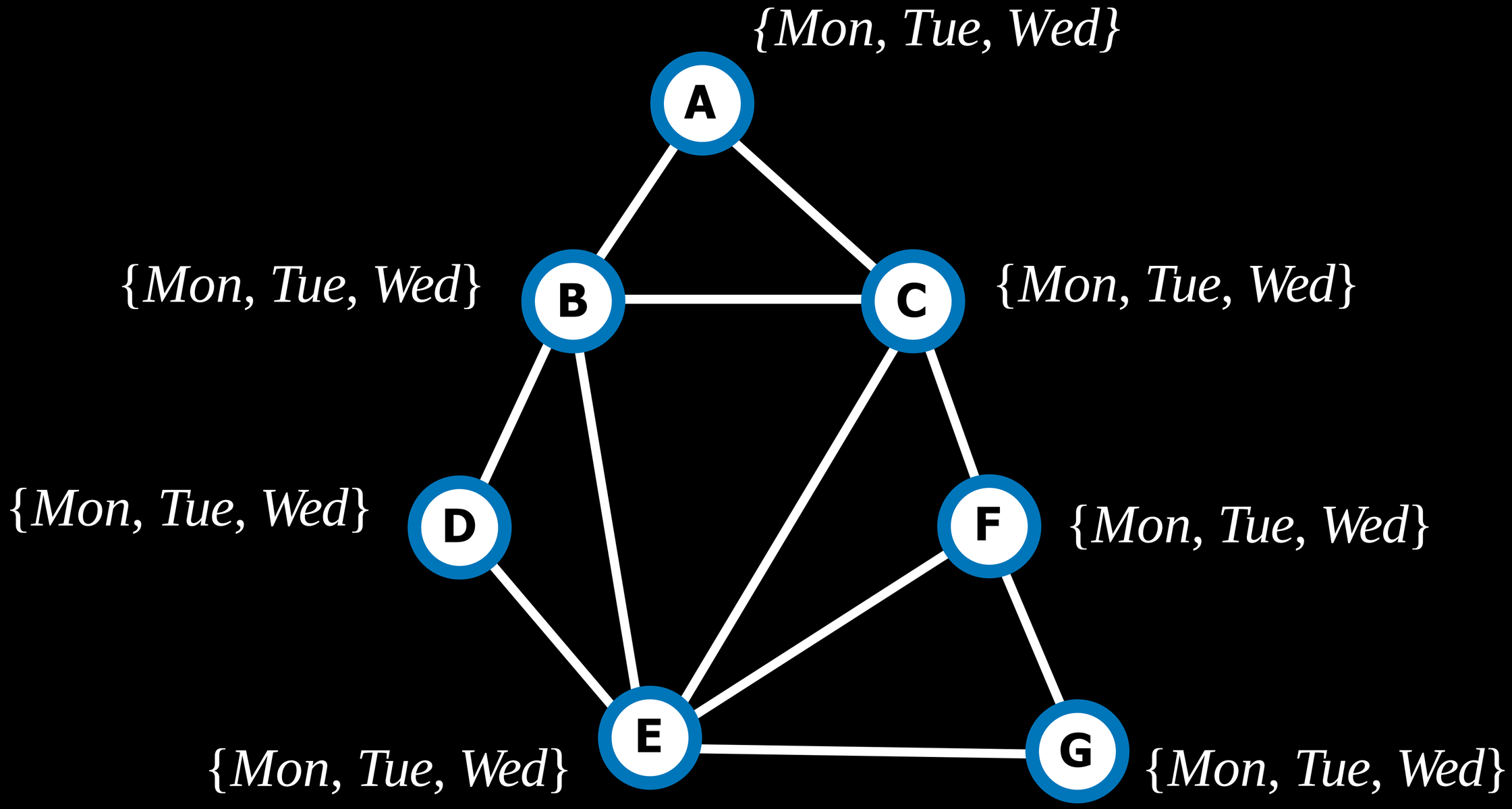
CSPs as Search Problems

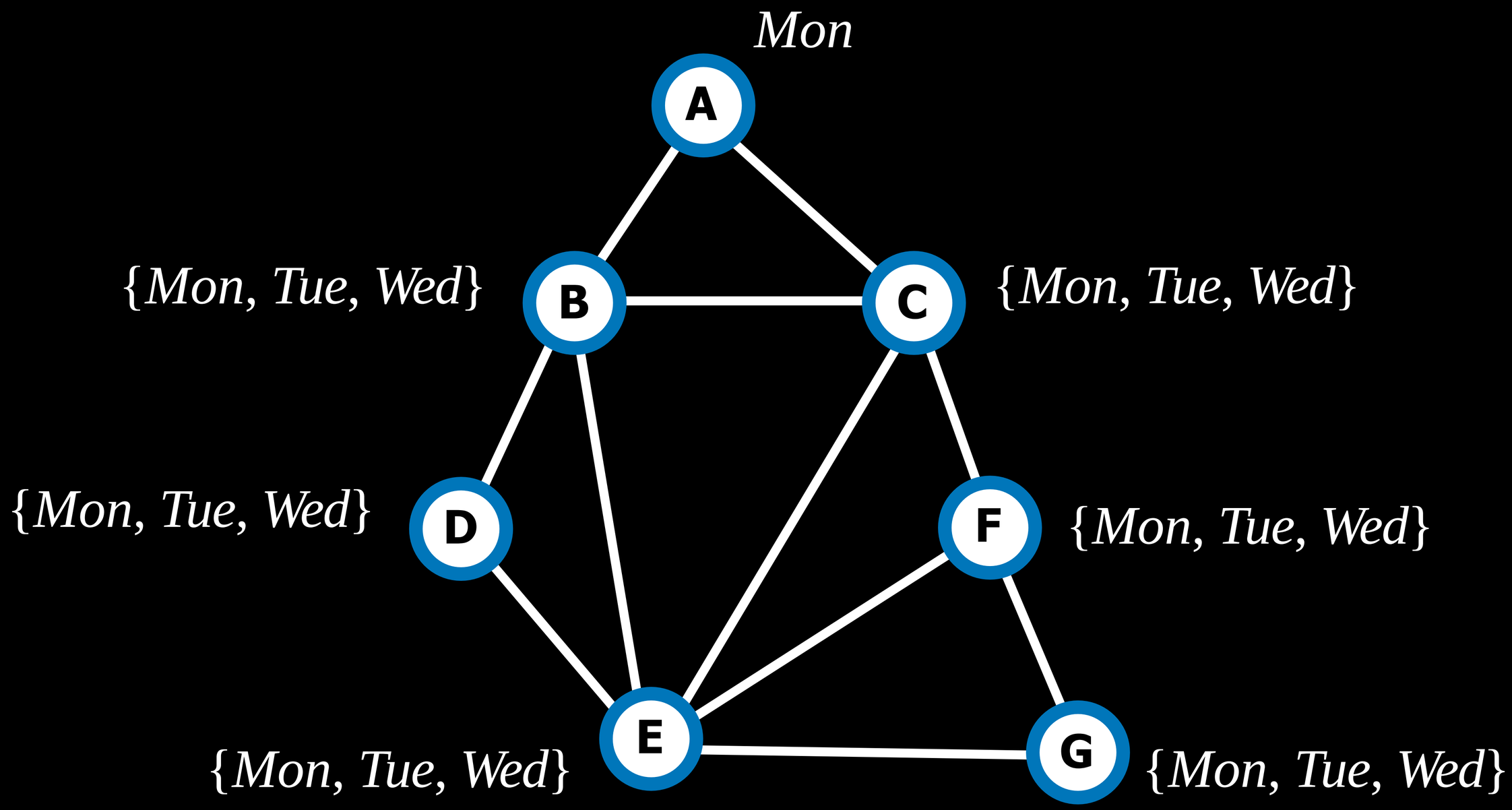
- initial state: empty assignment (no variables)
- actions: add a $\{variable = value\}$ to assignment
- transition model: shows how adding an assignment changes the assignment
- goal test: check if all variables assigned and constraints all satisfied
- path cost function: all paths have same cost

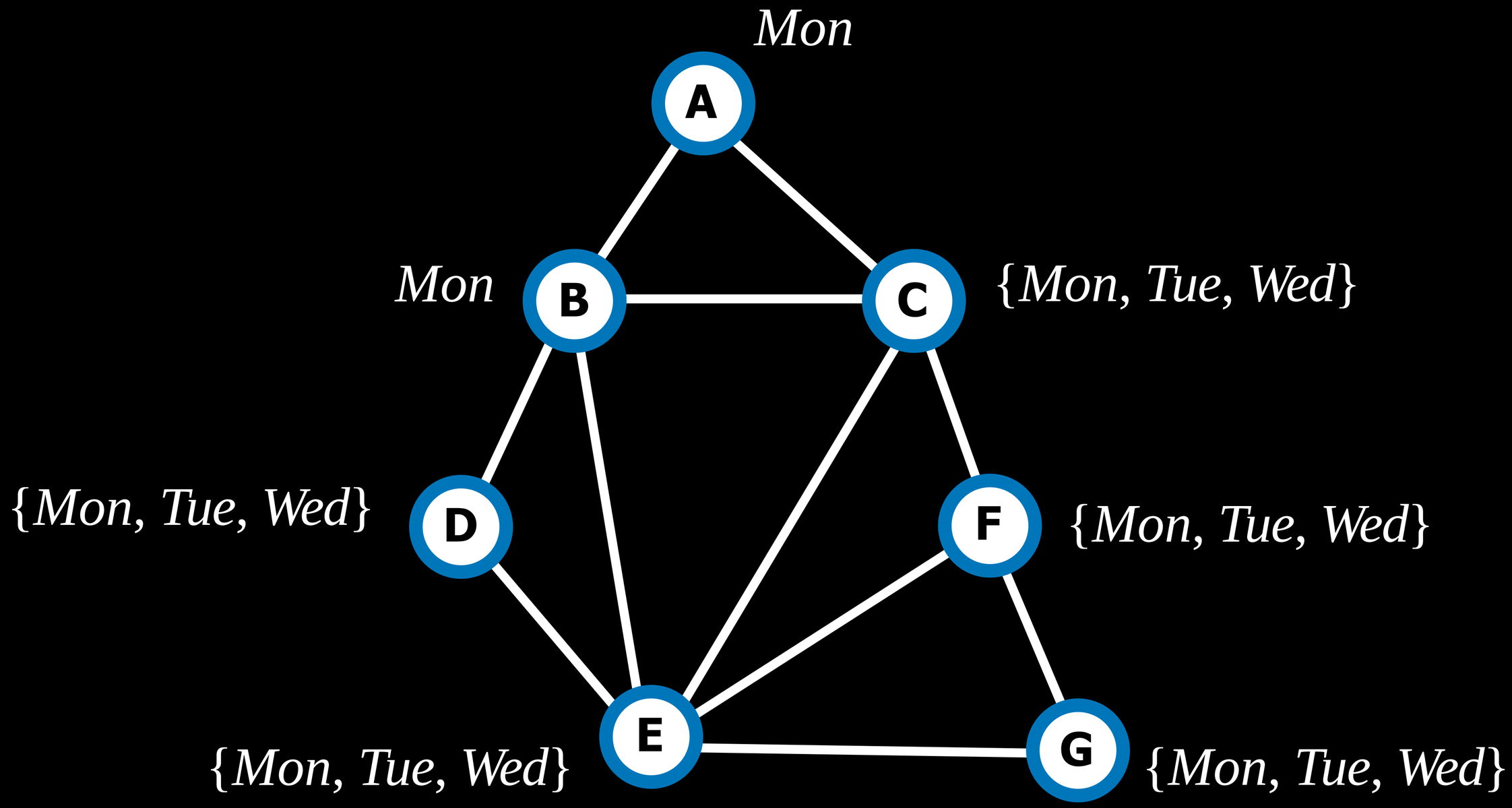
Backtracking Search

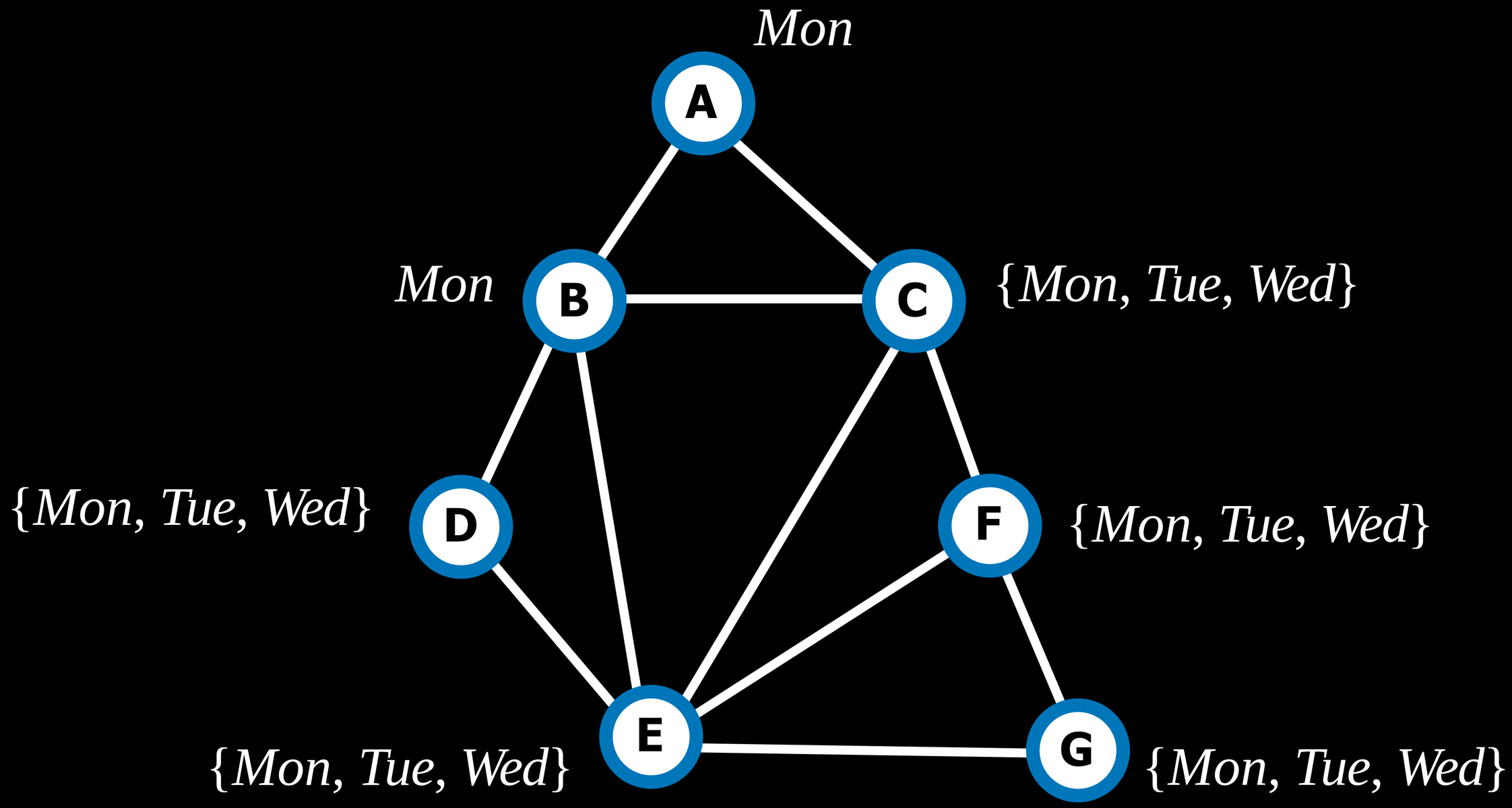
Backtracking Search

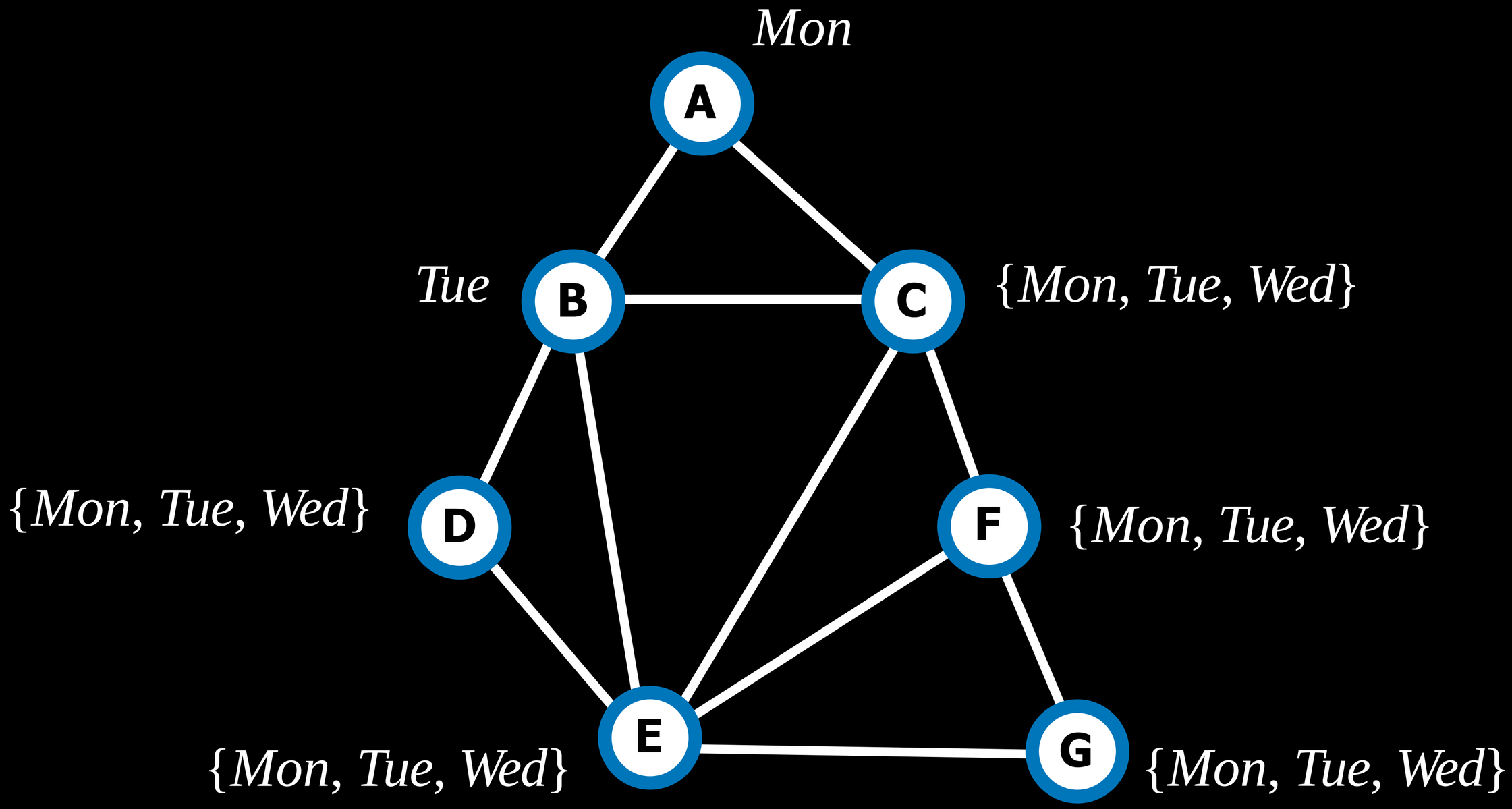
```
function BACKTRACK(assignment, csp):
    if assignment complete: return assignment
    var = SELECT-UNASSIGNED-VAR(assignment, csp)
    for value in DOMAIN-VALUES(var, assignment, csp):
        if value consistent with assignment:
            add {var = value} to assignment
            result = BACKTRACK(assignment, csp)
            if result ≠ failure: return result
        remove {var = value} from assignment
    return failure
```

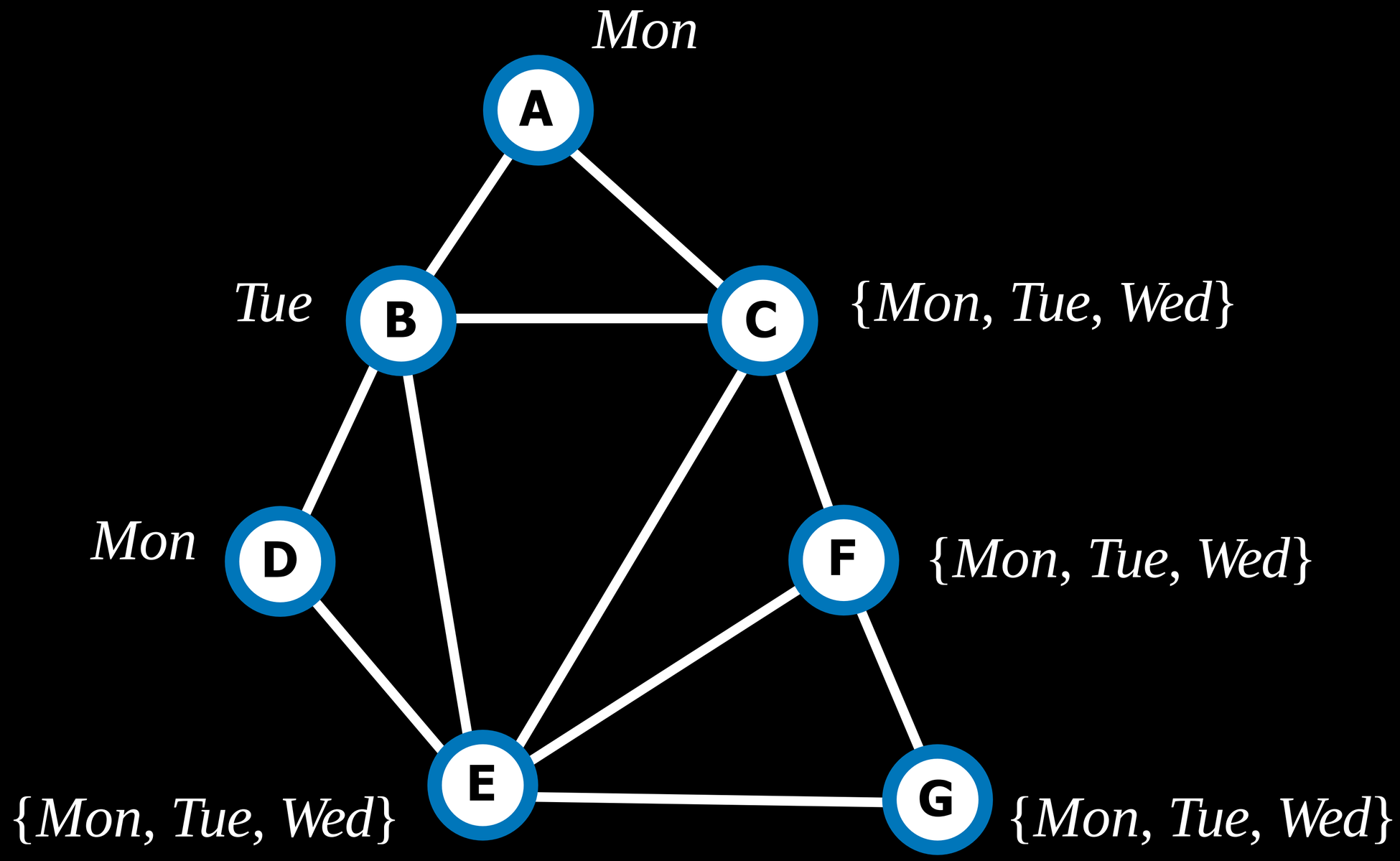

{Mon, Tue, Wed}
A
{Mon, Tue, Wed}
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

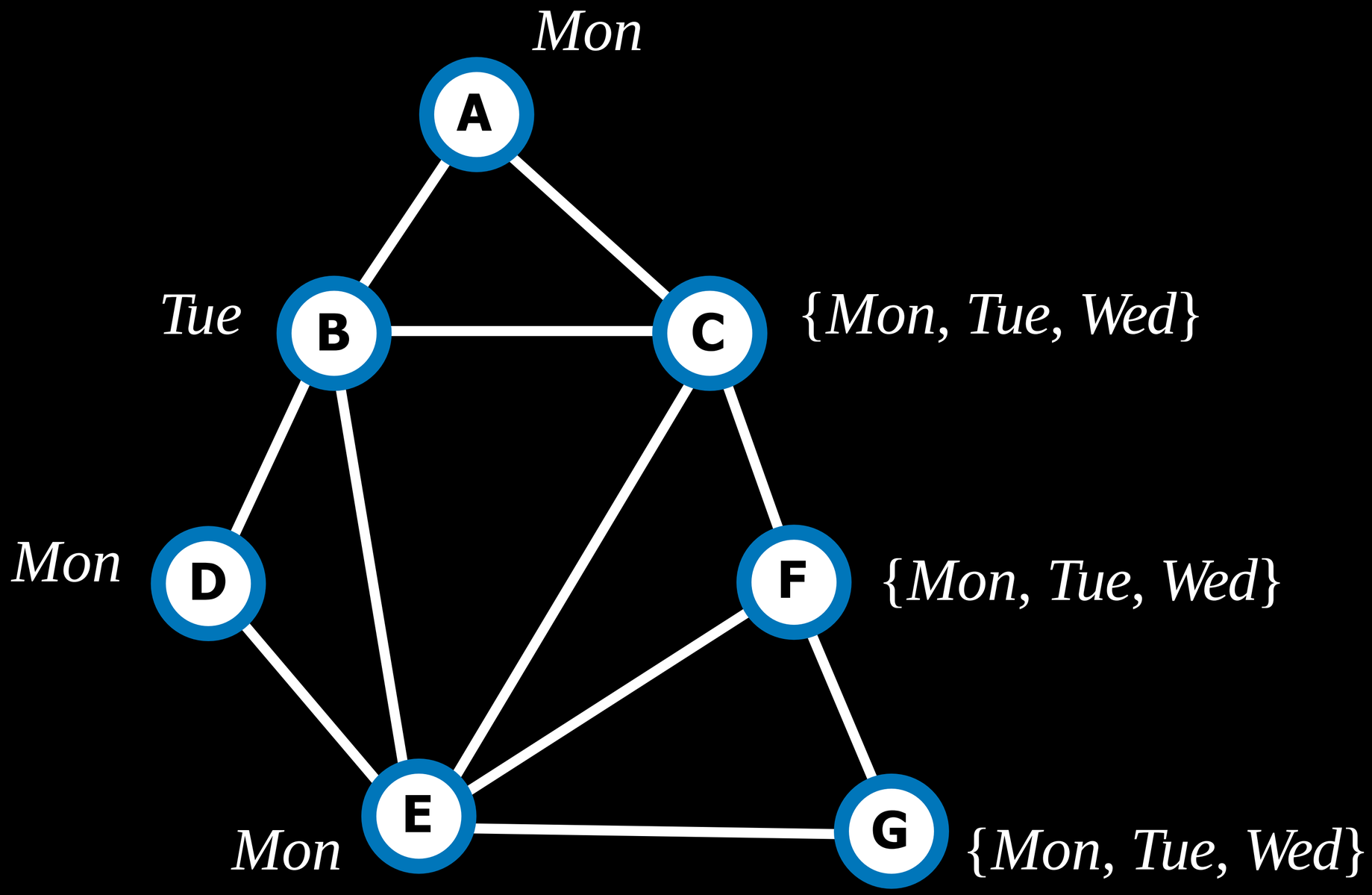

Mon
A
{Mon, Tue, Wed}
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

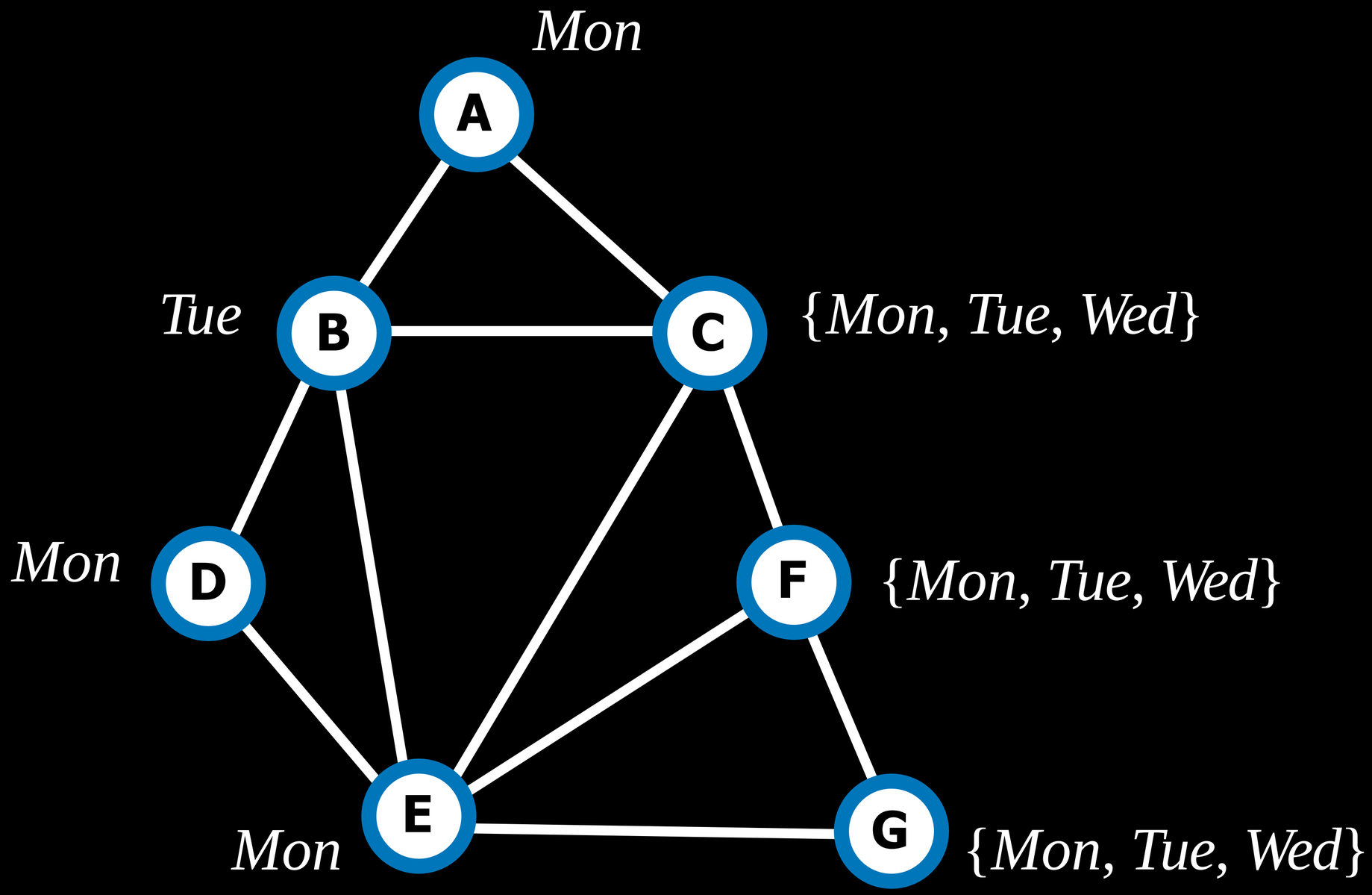

Mon
A
Mon
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

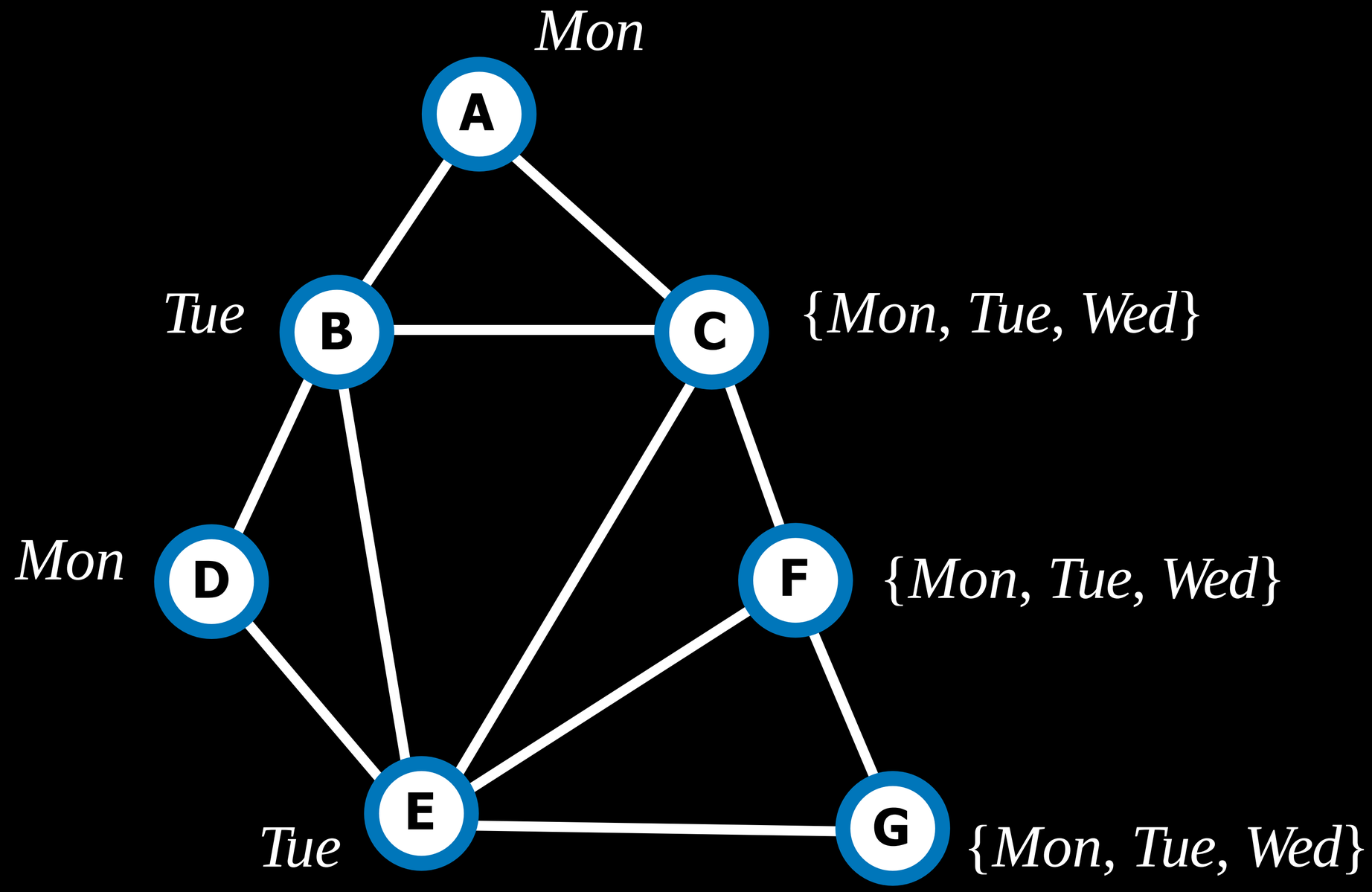

Mon
A
Mon
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

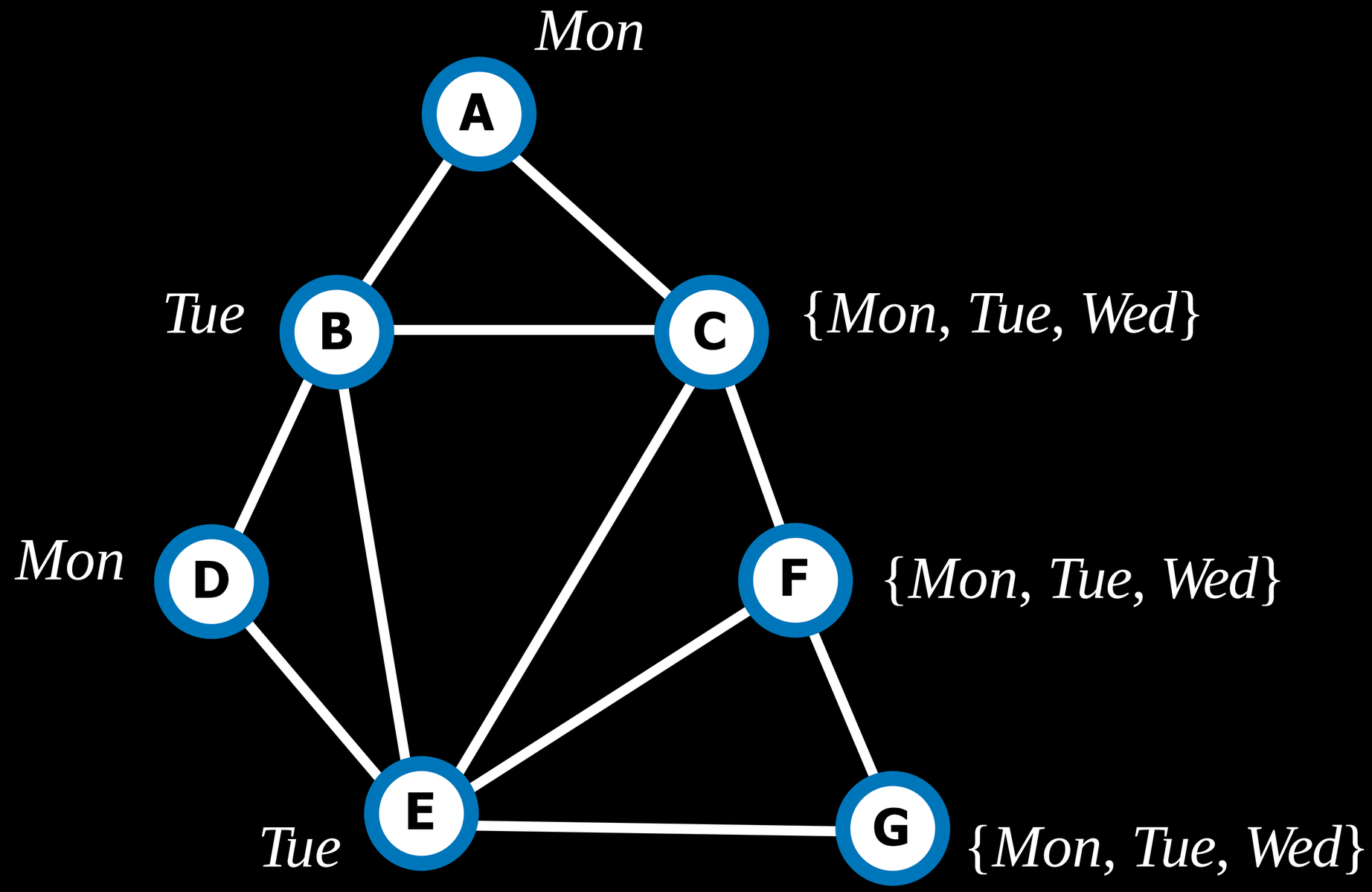

Mon
A
Tue
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

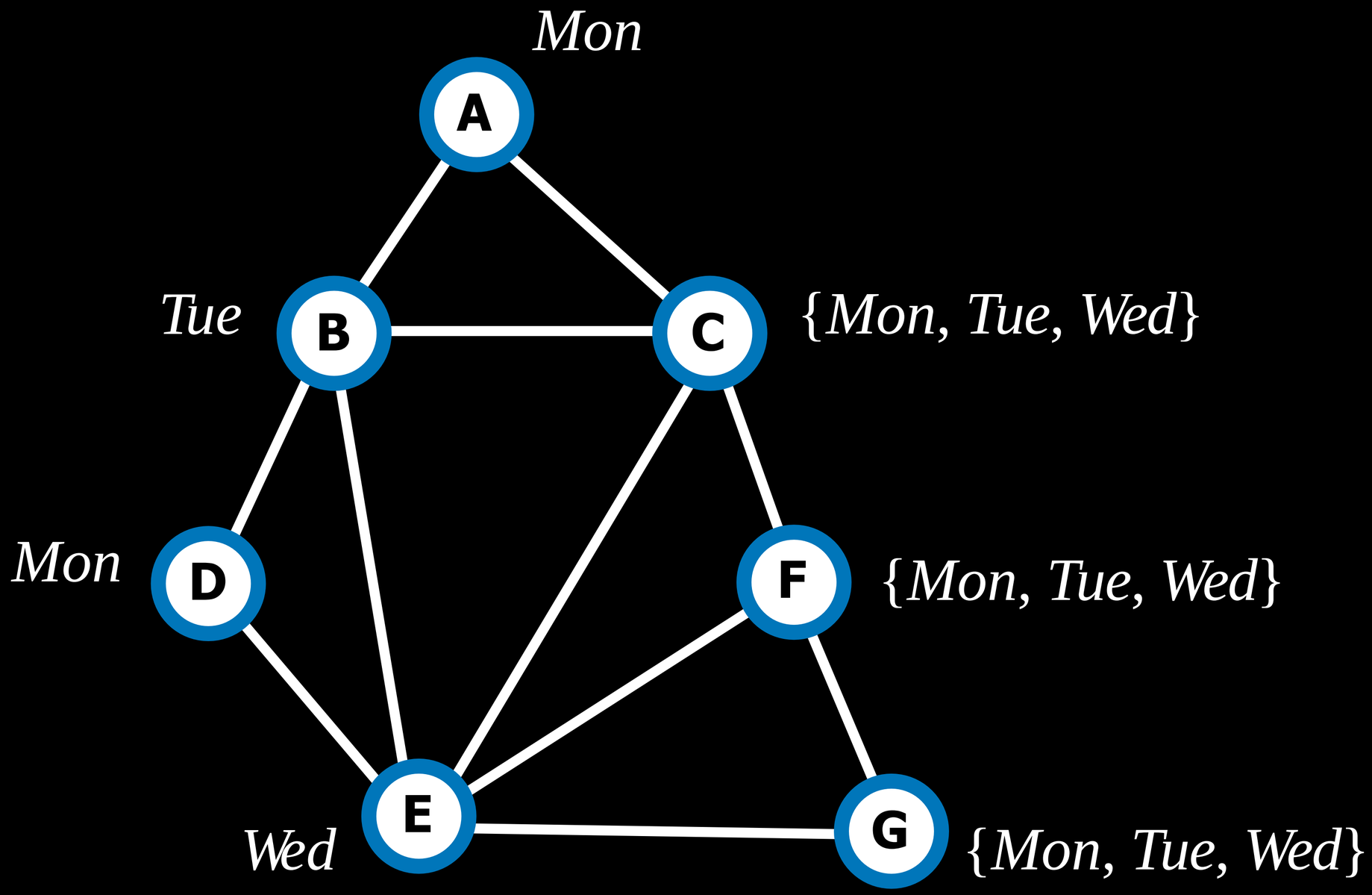

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}

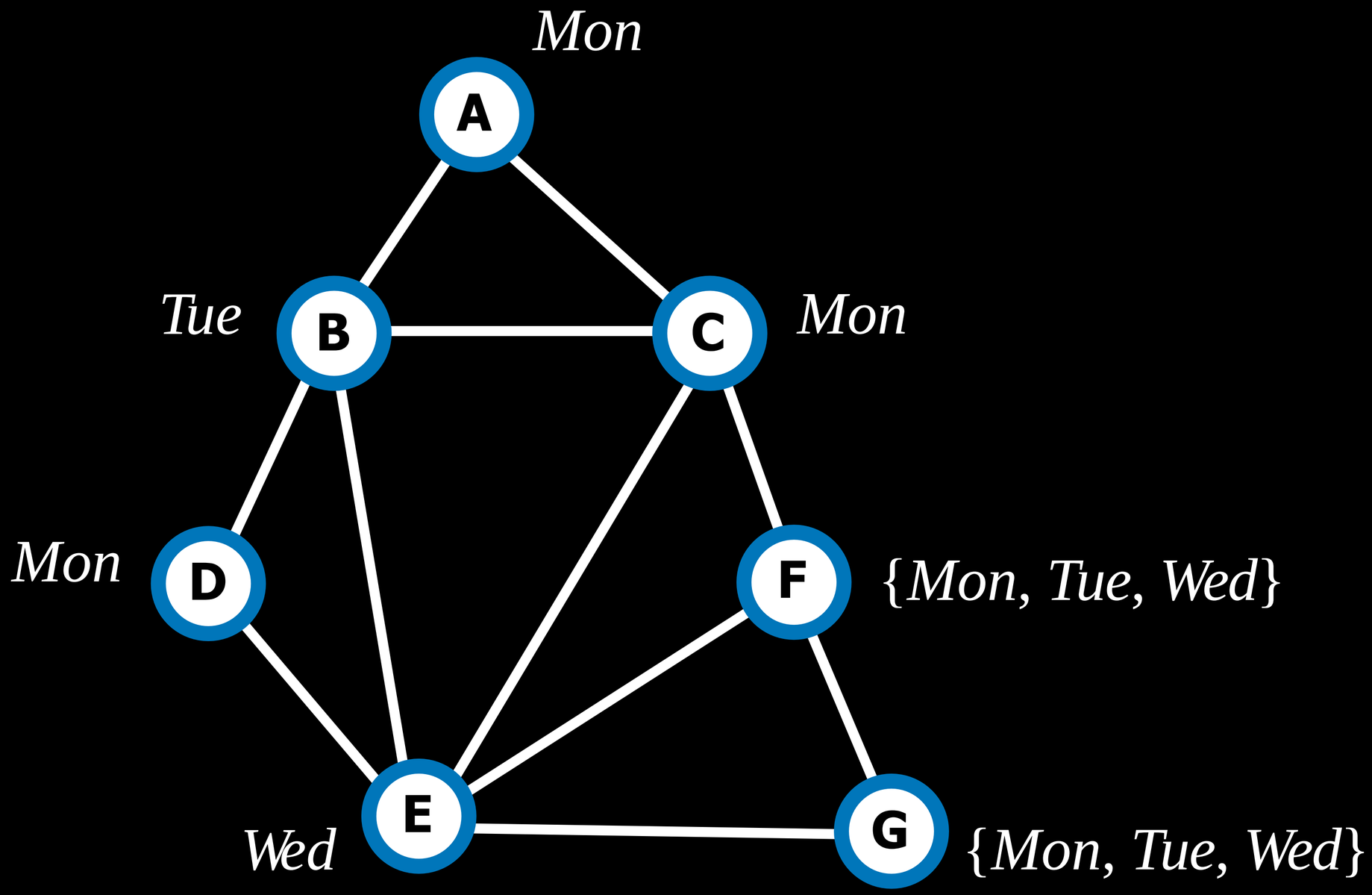

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
Mon
E
G
{Mon, Tue, Wed}

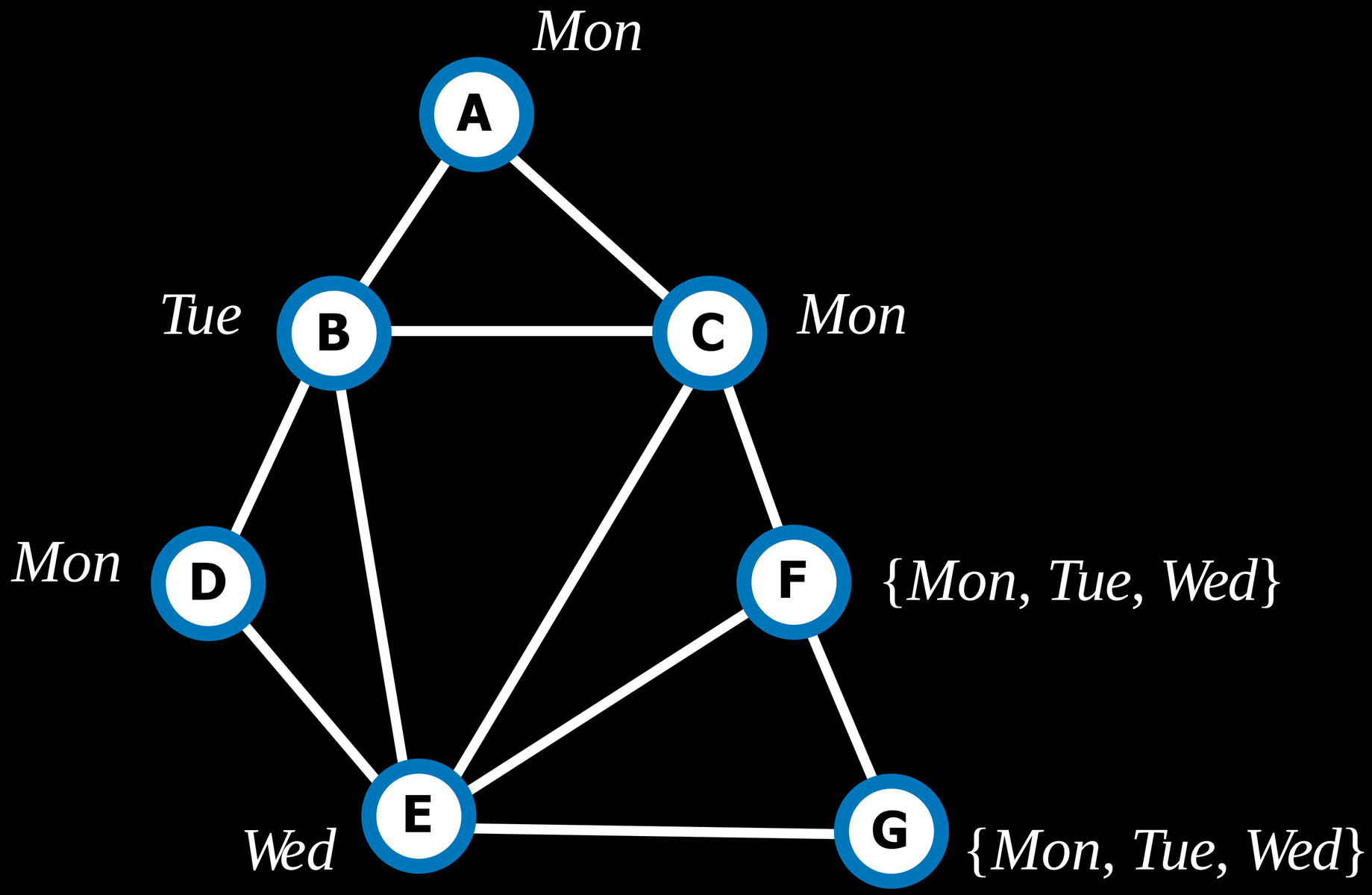

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
Mon
E
G
{Mon, Tue, Wed}

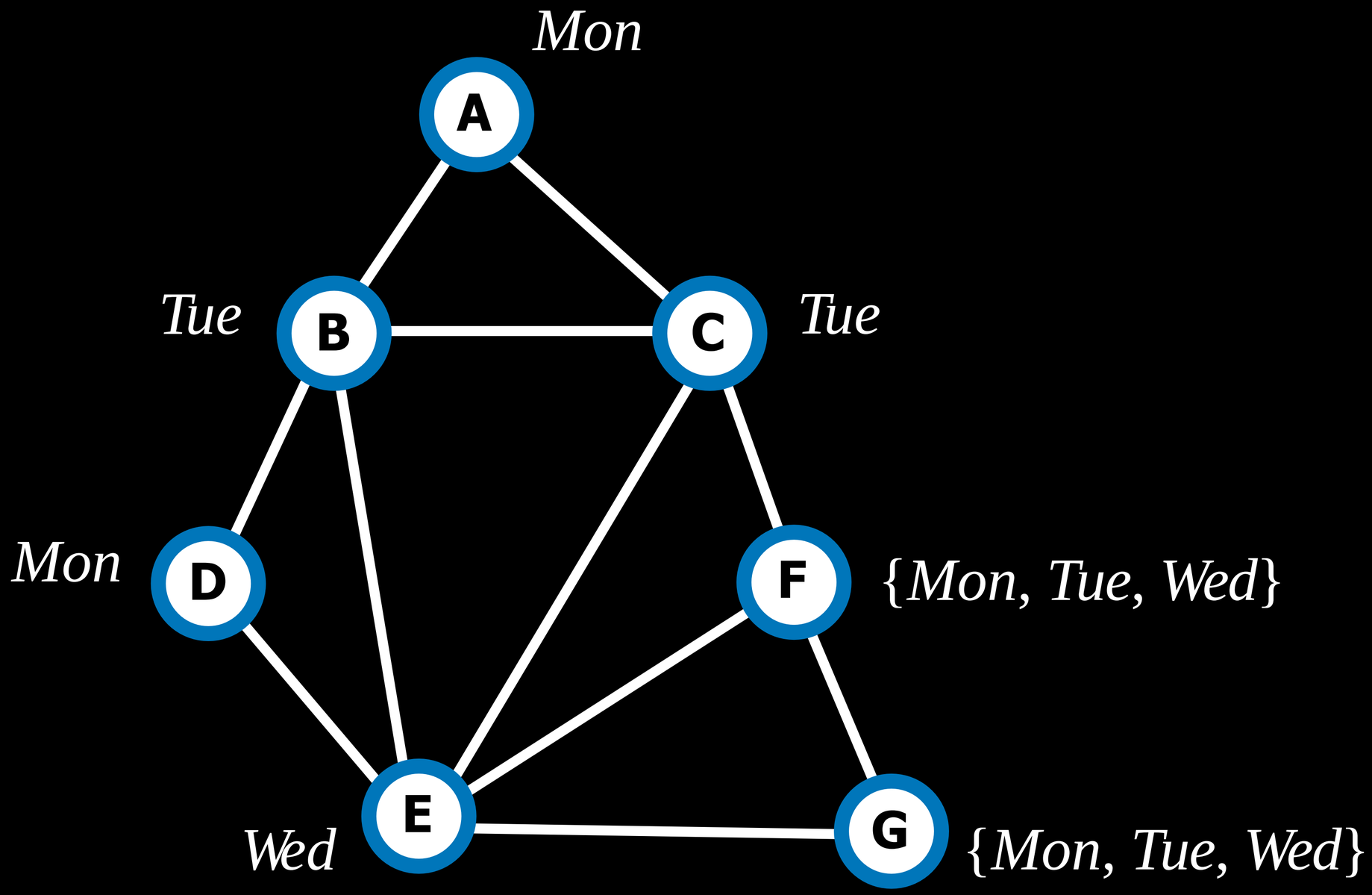

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
E
Tue
G
{Mon, Tue, Wed}

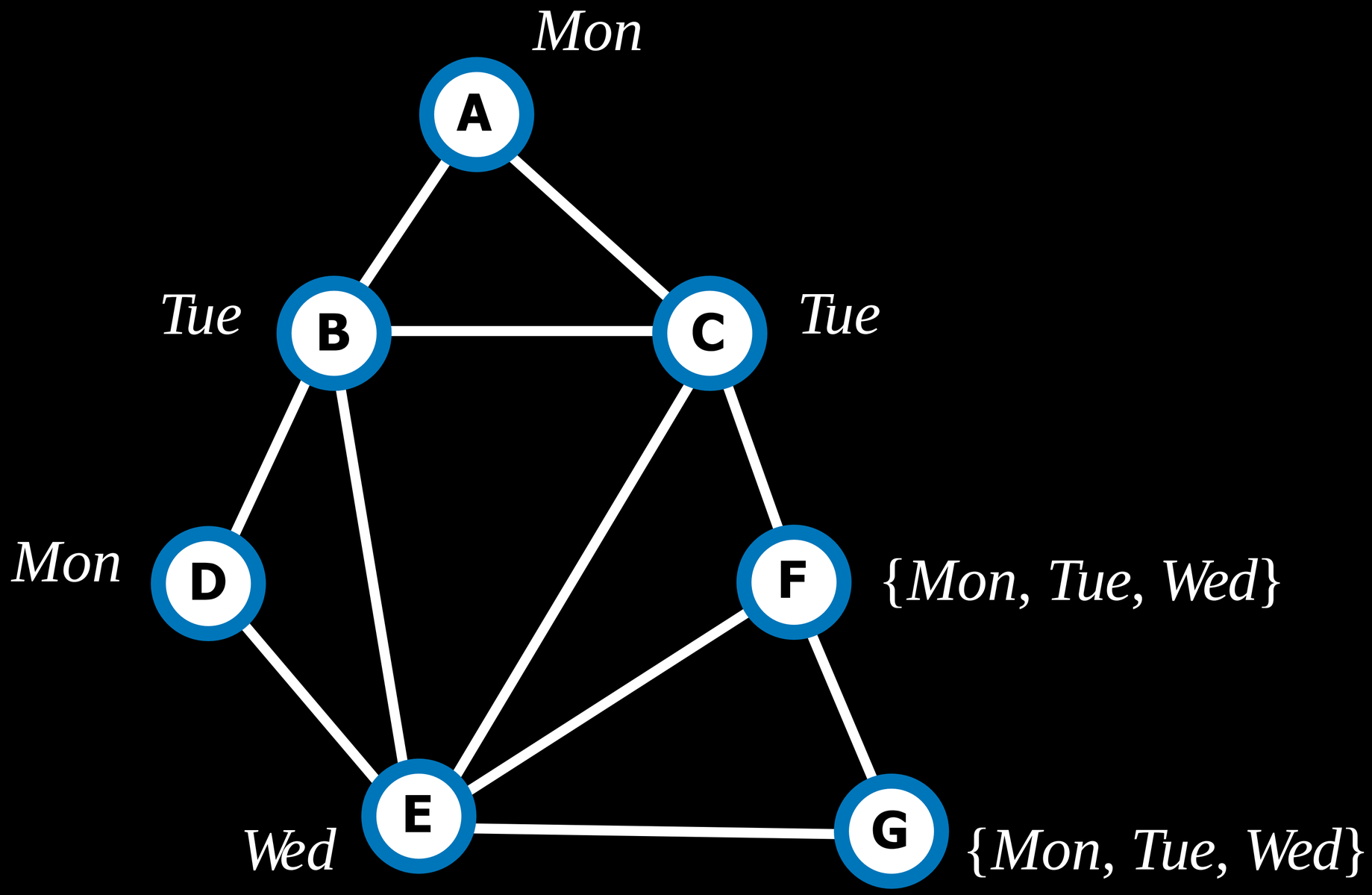

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
E
Tue
G
{Mon, Tue, Wed}

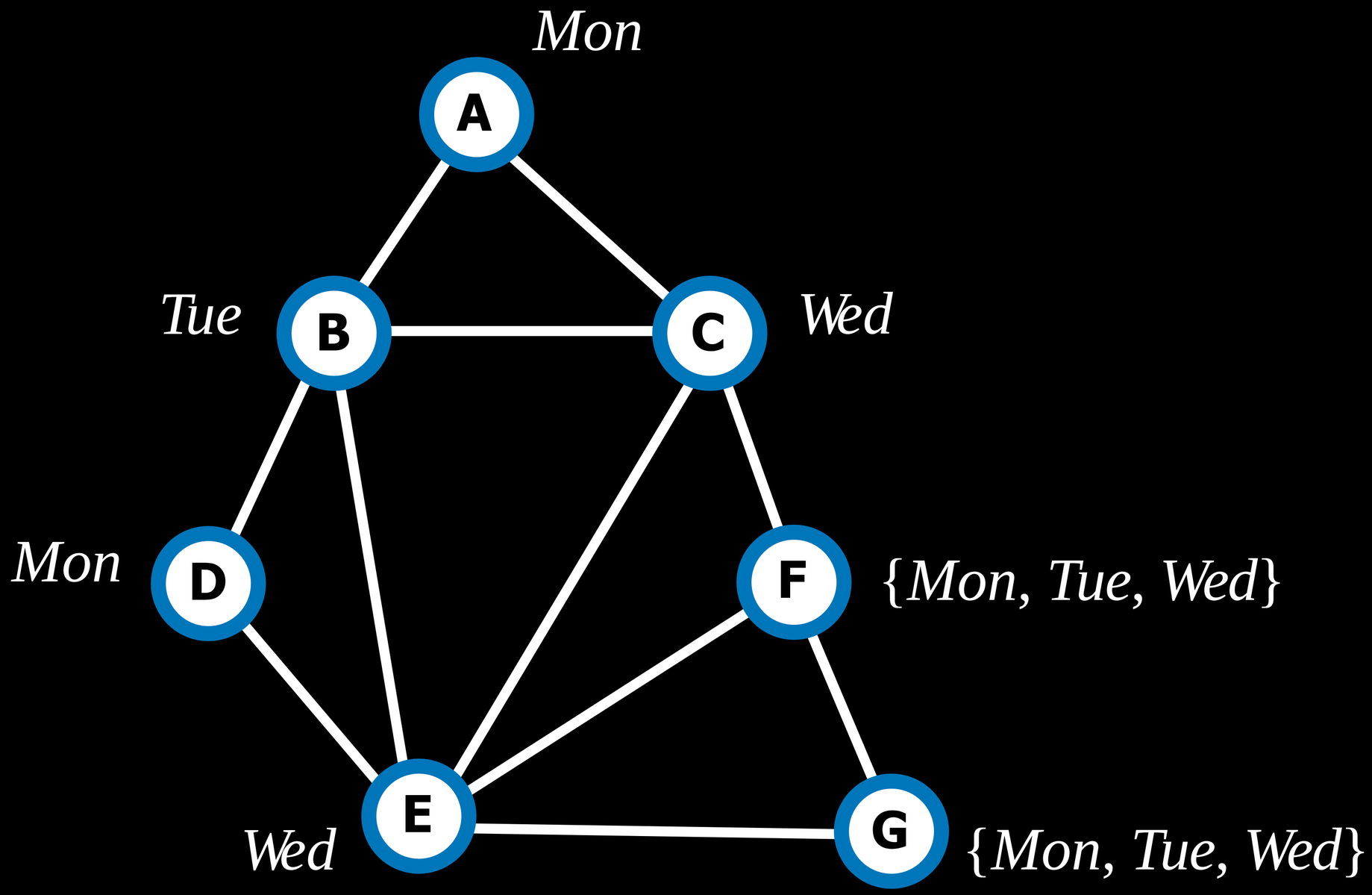

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
E
G
Wed
{Mon, Tue, Wed}

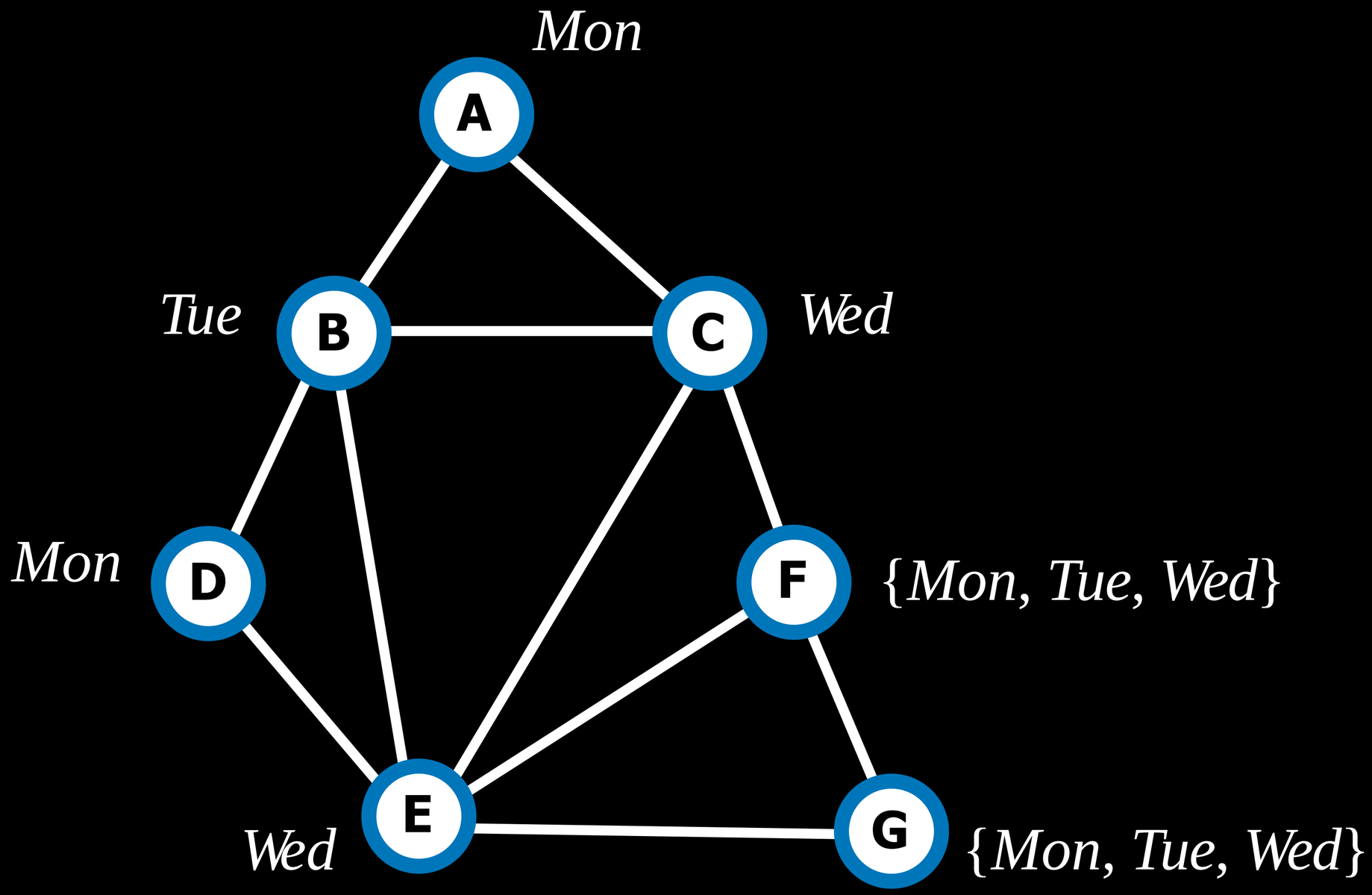

Mon
A
Tue
B
C
Mon
Mon
D
F
{Mon, Tue, Wed}
E
G
Wed
{Mon, Tue, Wed}

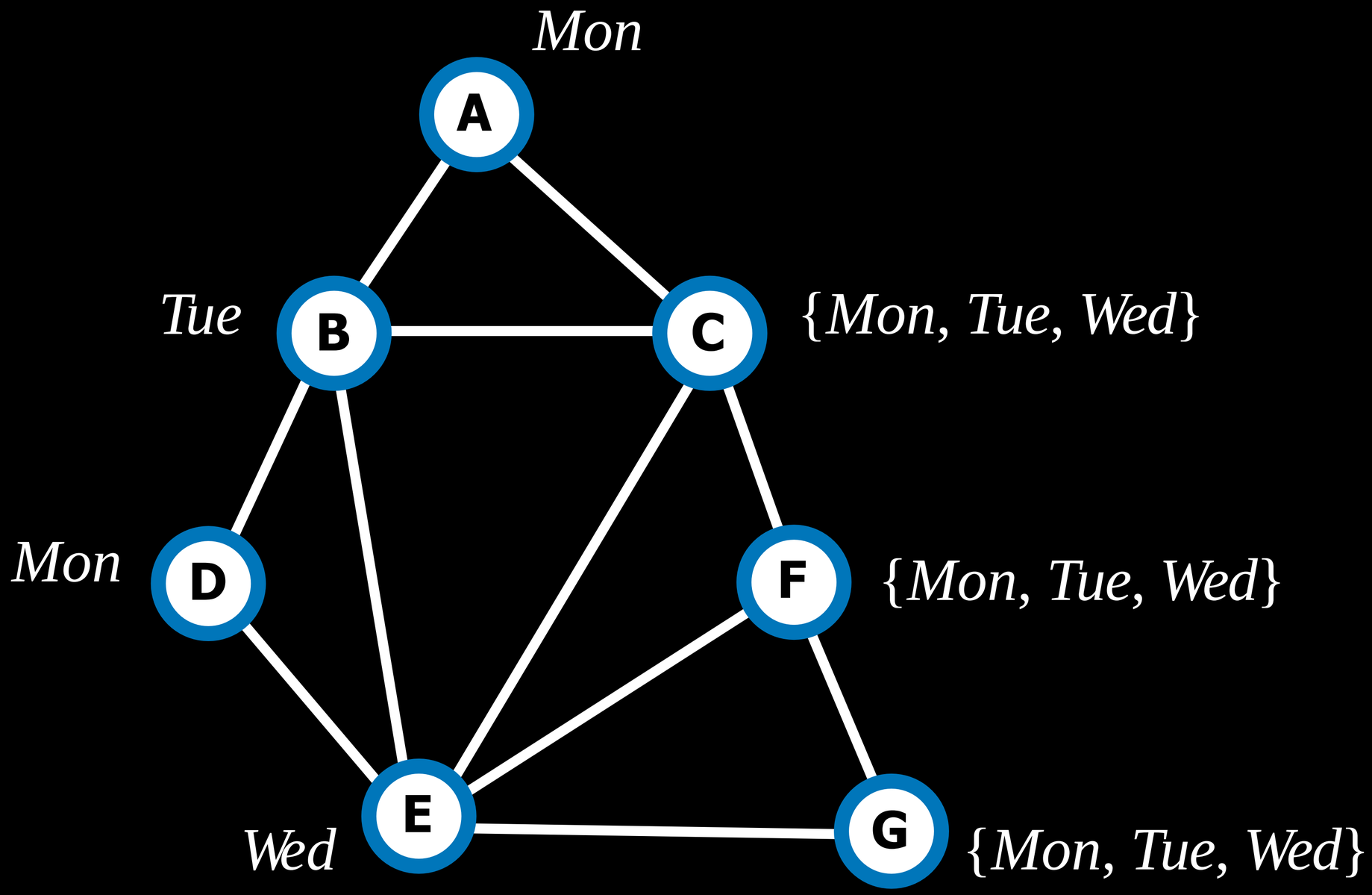

Mon
A
Tue
B
C
Mon
Mon
D
F
{Mon, Tue, Wed}
E
G
Wed
{Mon, Tue, Wed}

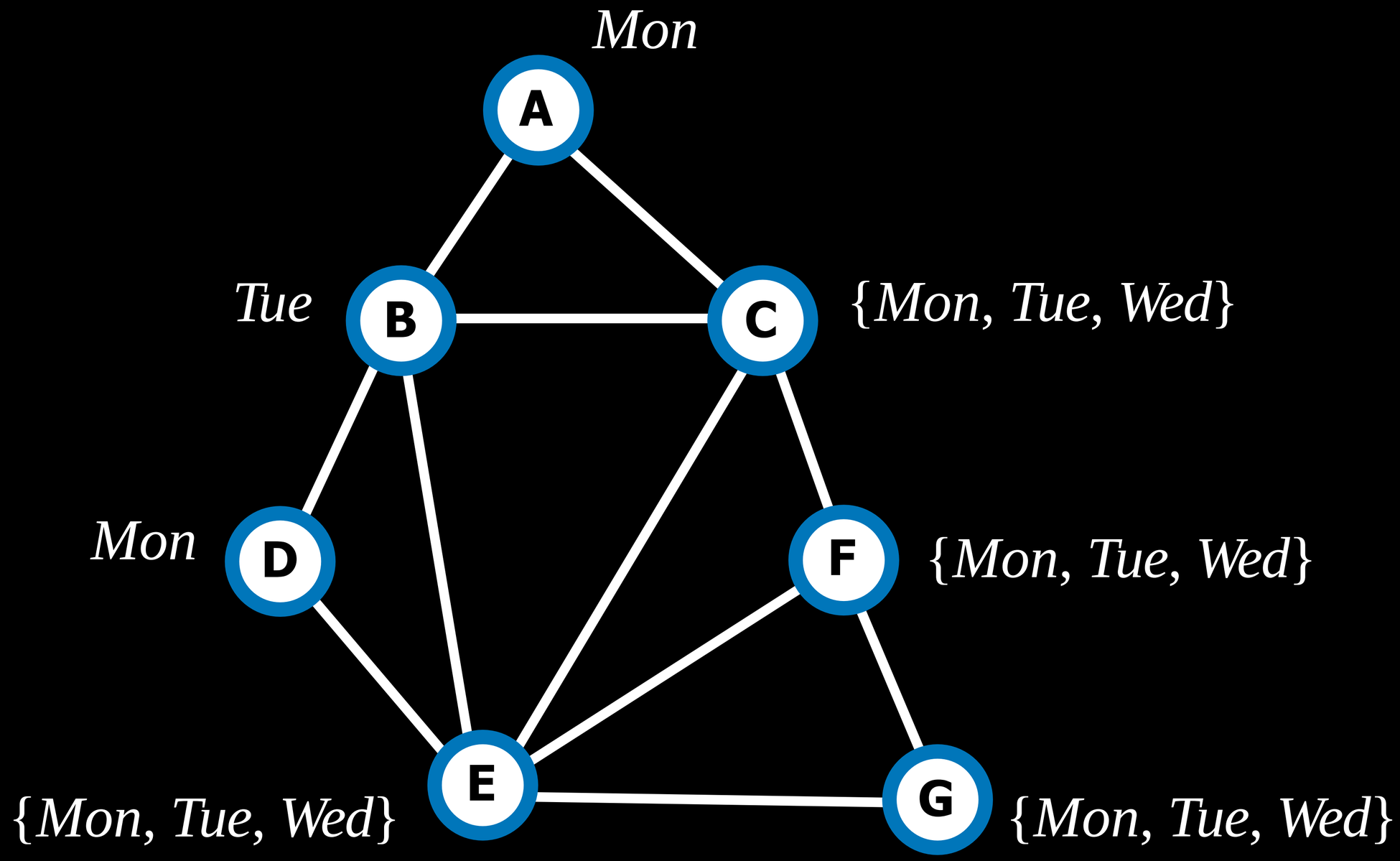

Mon
A
Tue
B
C
Tue
Mon
D
F
{Mon, Tue, Wed}
E
G
Wed
{Mon, Tue, Wed}

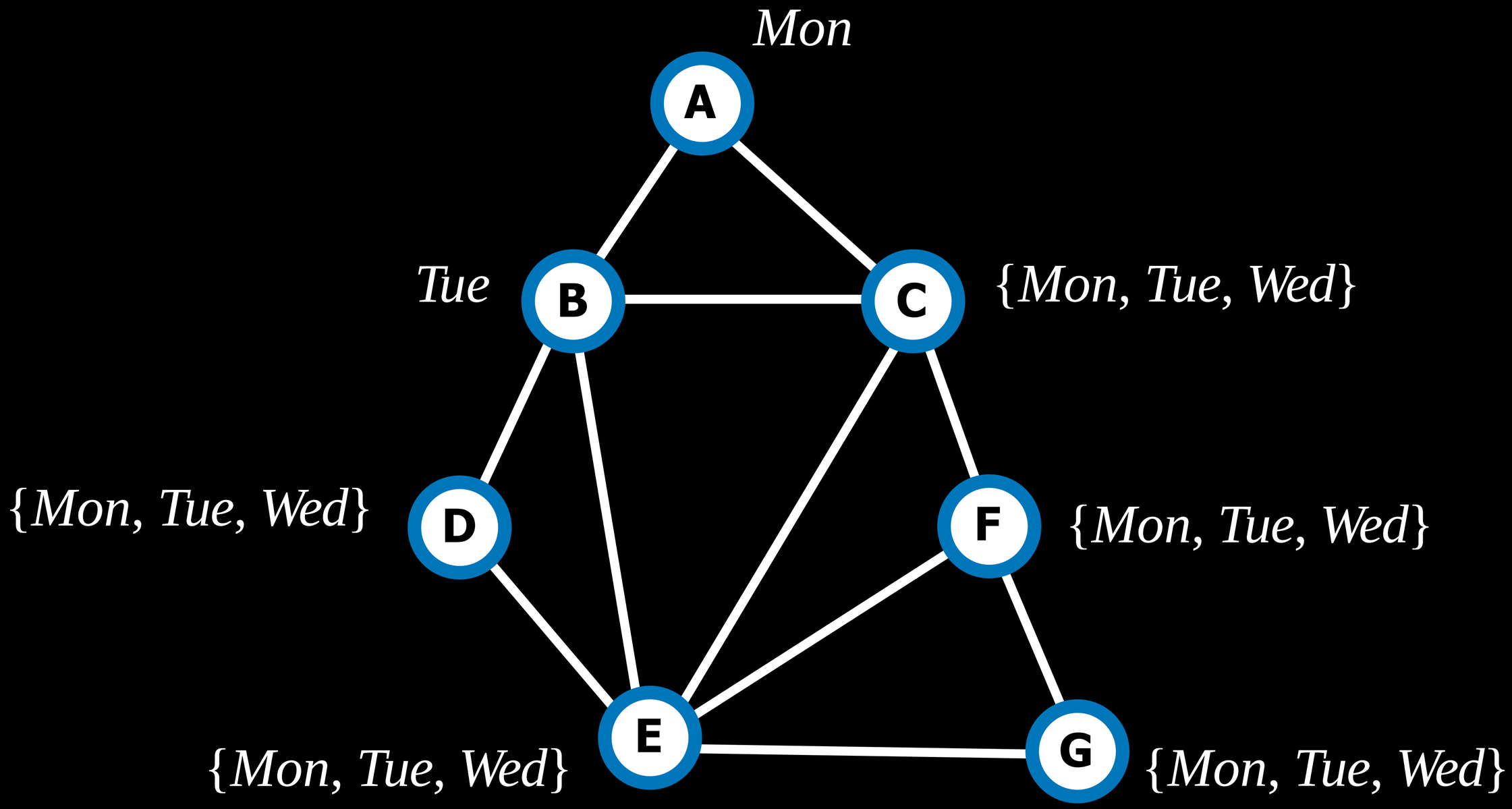

Mon
A
Tue
B
C
Tue
Mon
D
F
{Mon, Tue, Wed}
E
G
Wed
{Mon, Tue, Wed}

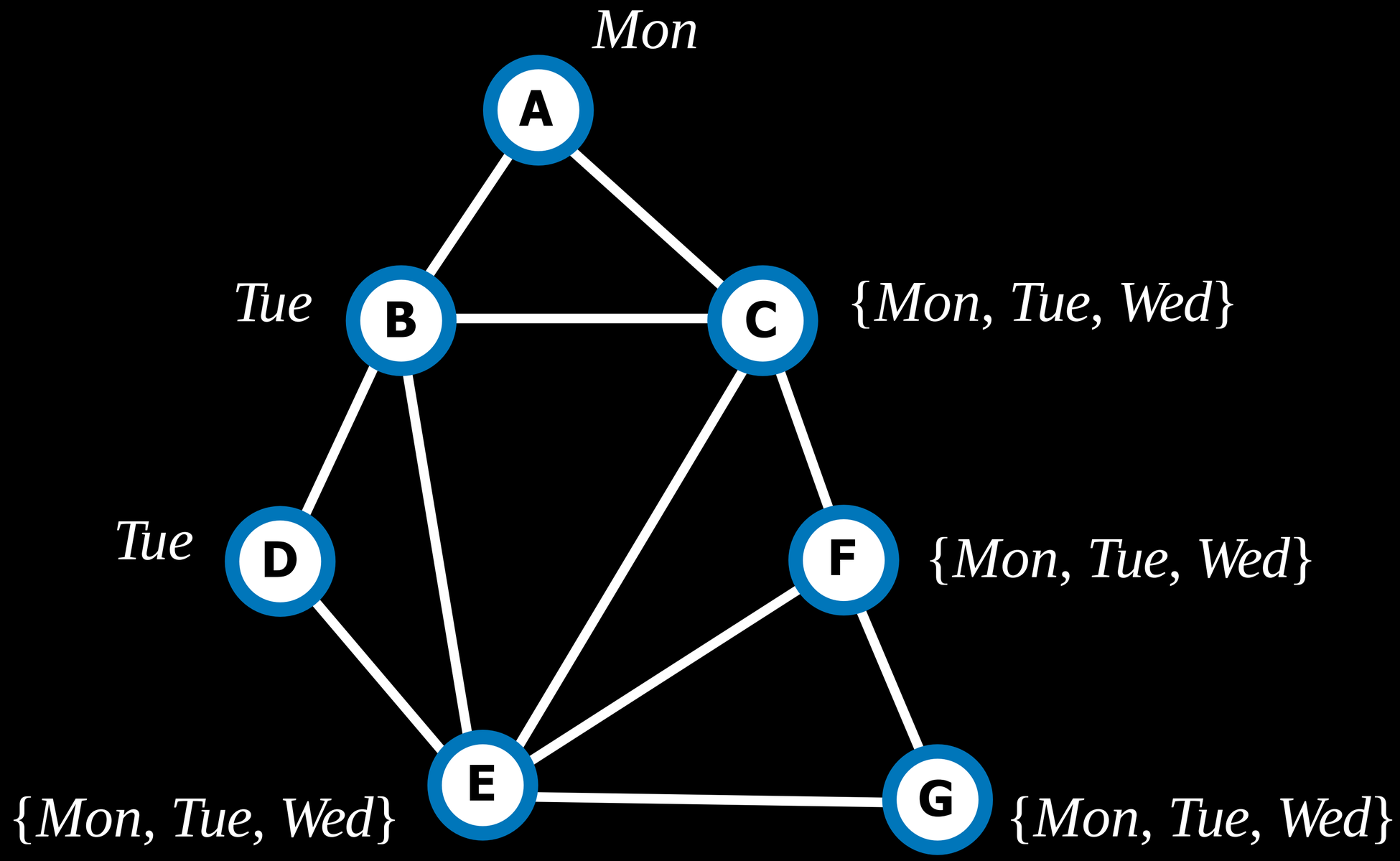

Mon
A
Tue
B
C
Wed
Mon
D
F
{Mon, Tue, Wed}
E
G
Wed
{Mon, Tue, Wed}

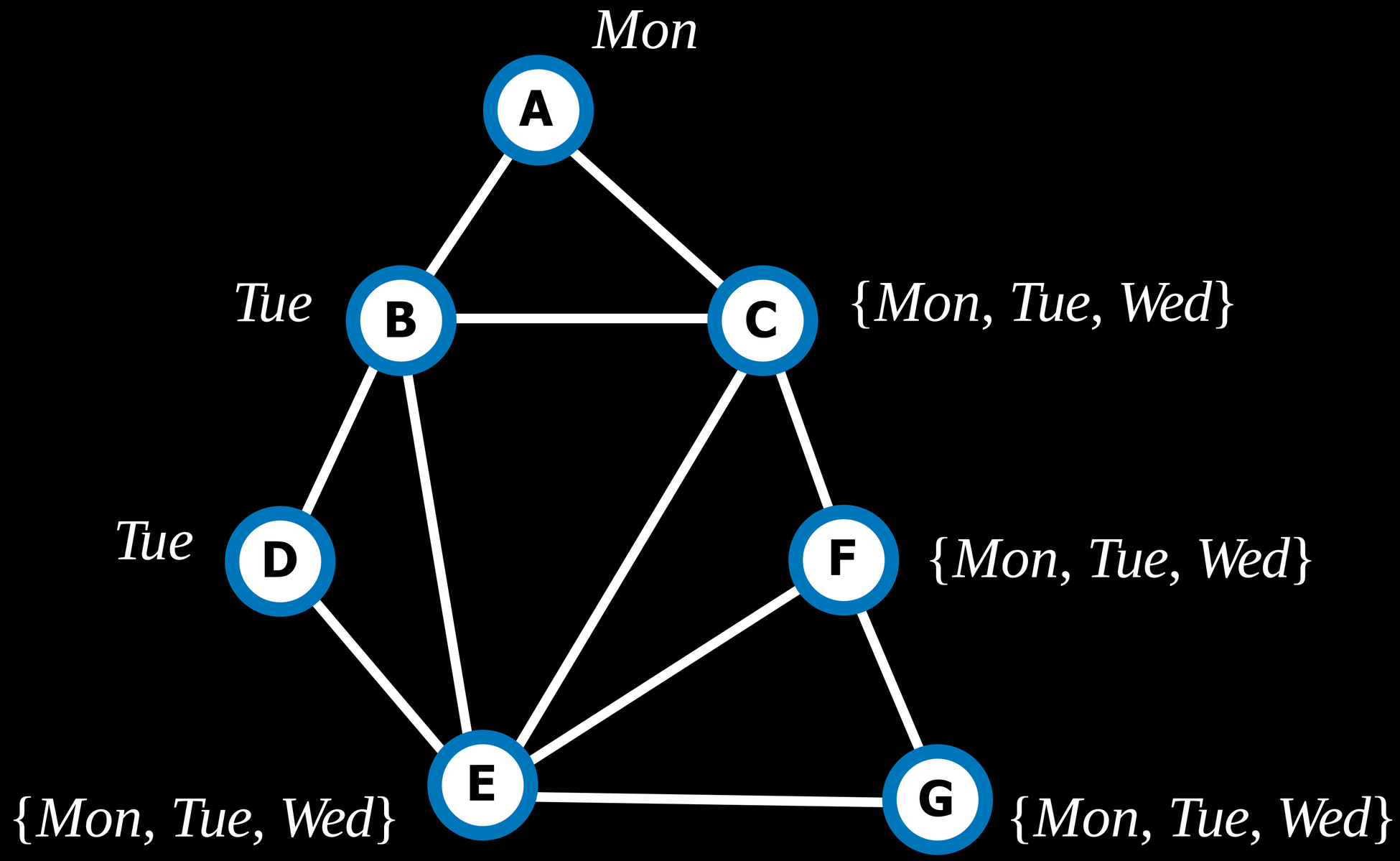

Mon
A
Tue
B
C
Wed
Mon
D
F
{Mon, Tue, Wed}
E
G
Wed
{Mon, Tue, Wed}

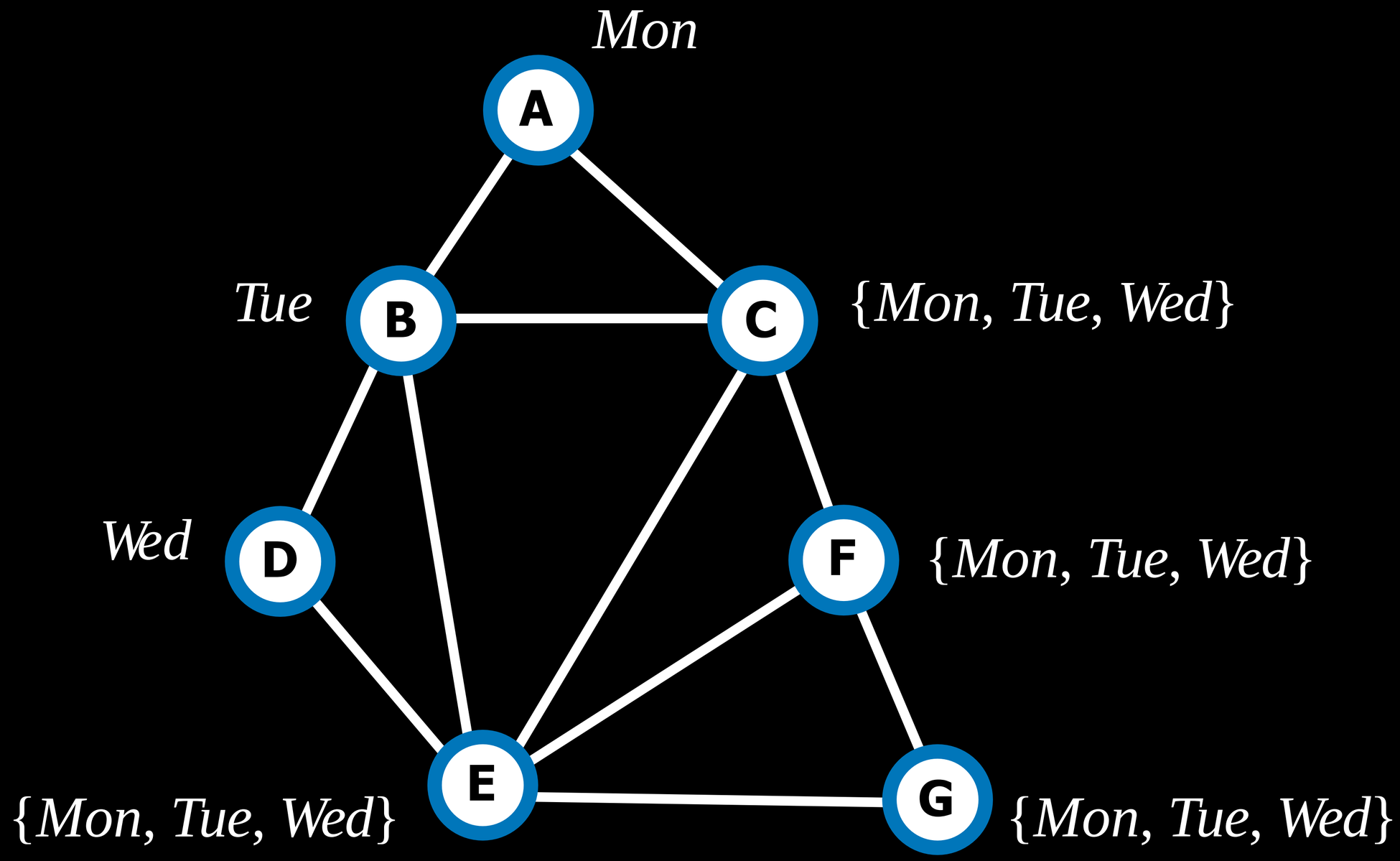

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
E
G
Wed
{Mon, Tue, Wed}

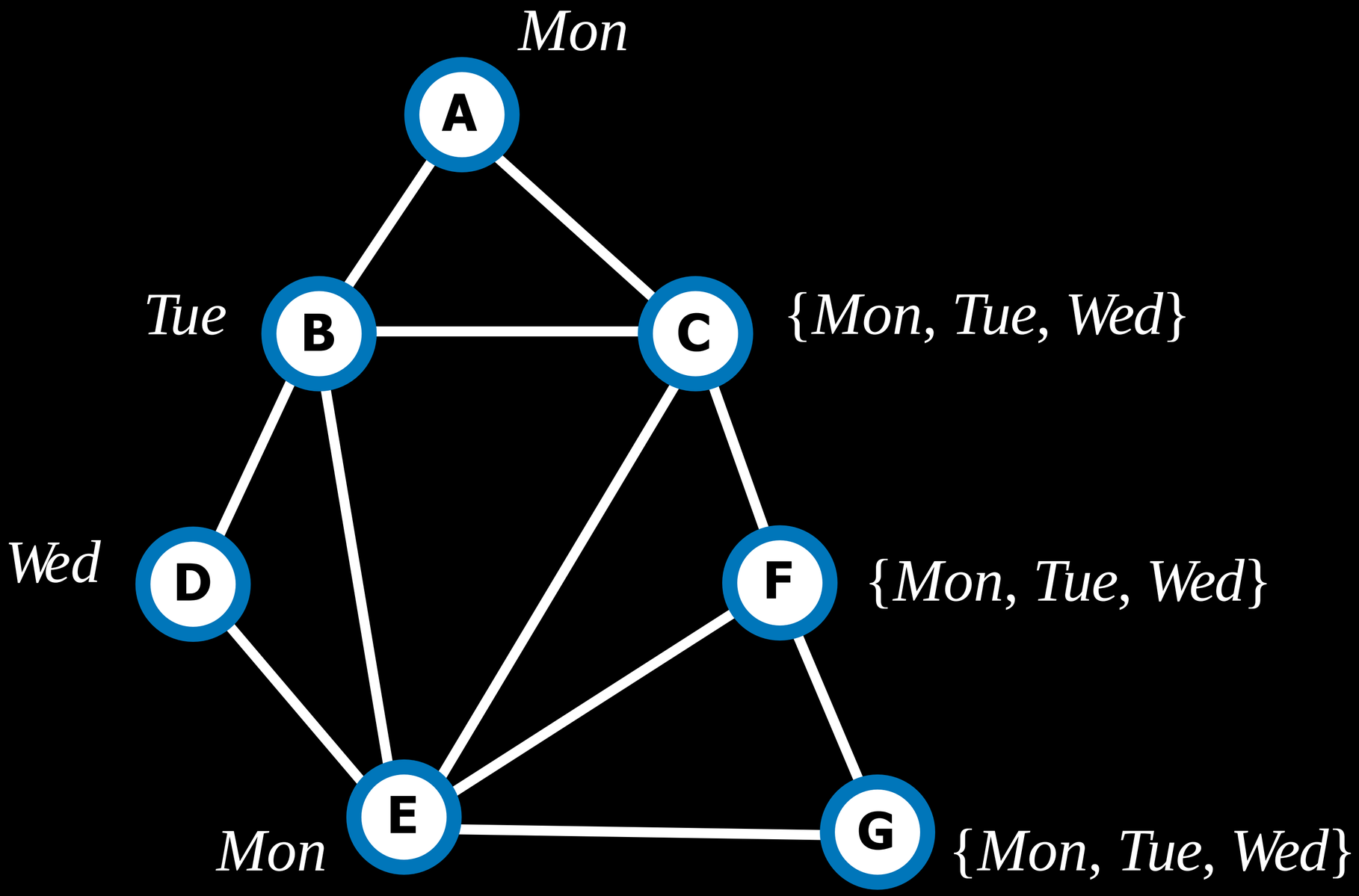

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}

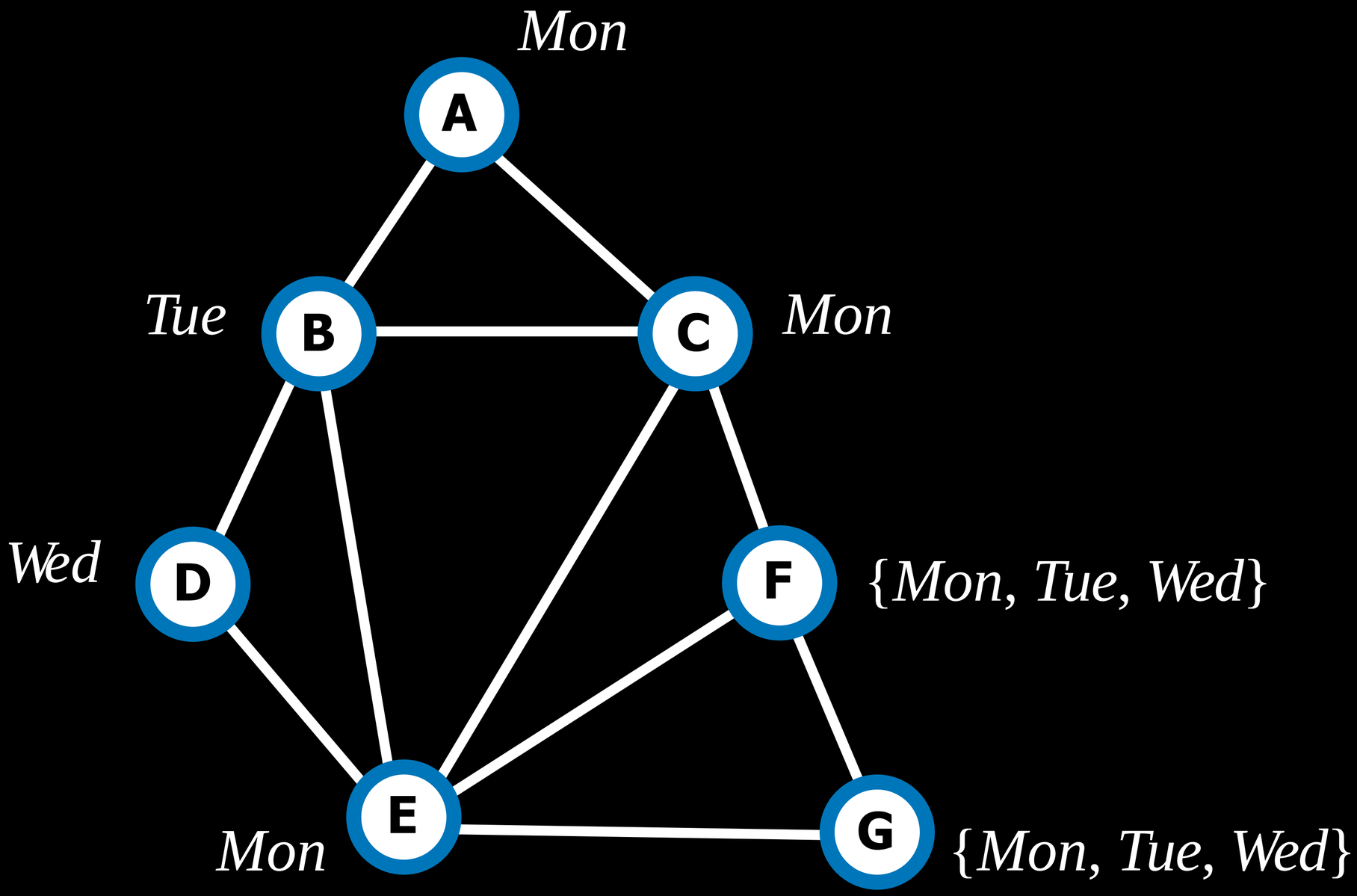

Mon
A
Tue
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

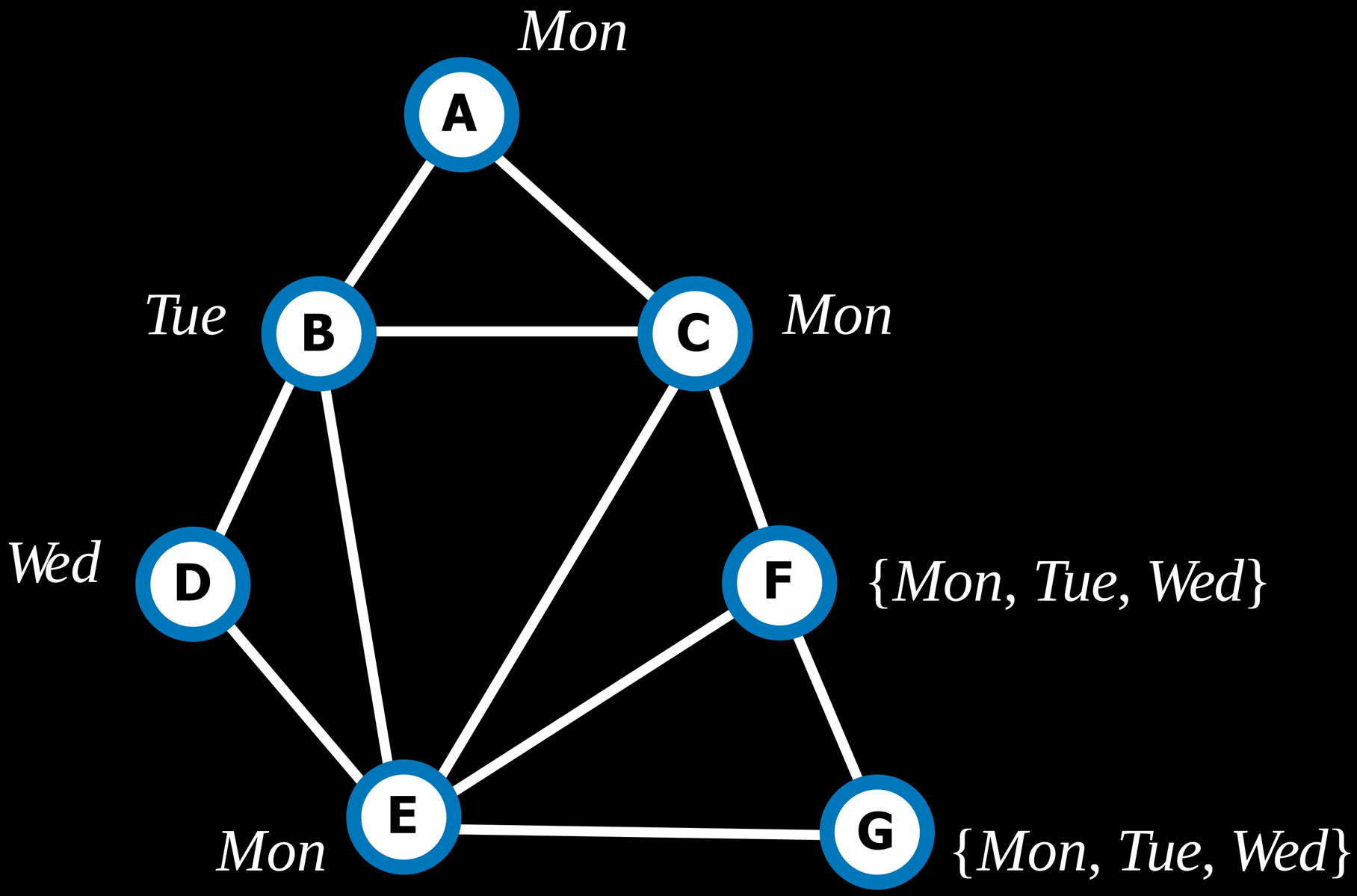

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Tue
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}

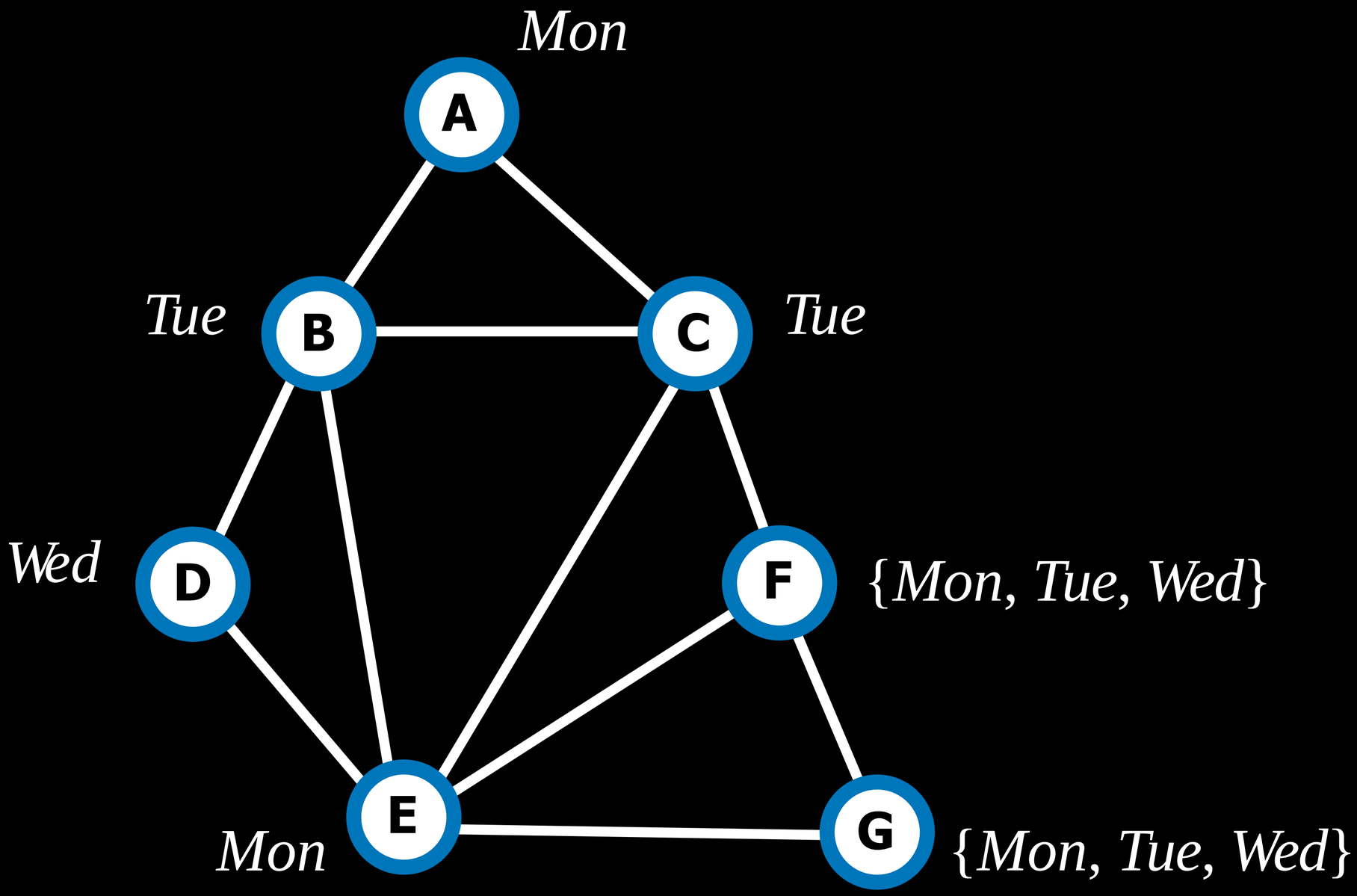

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Tue
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}

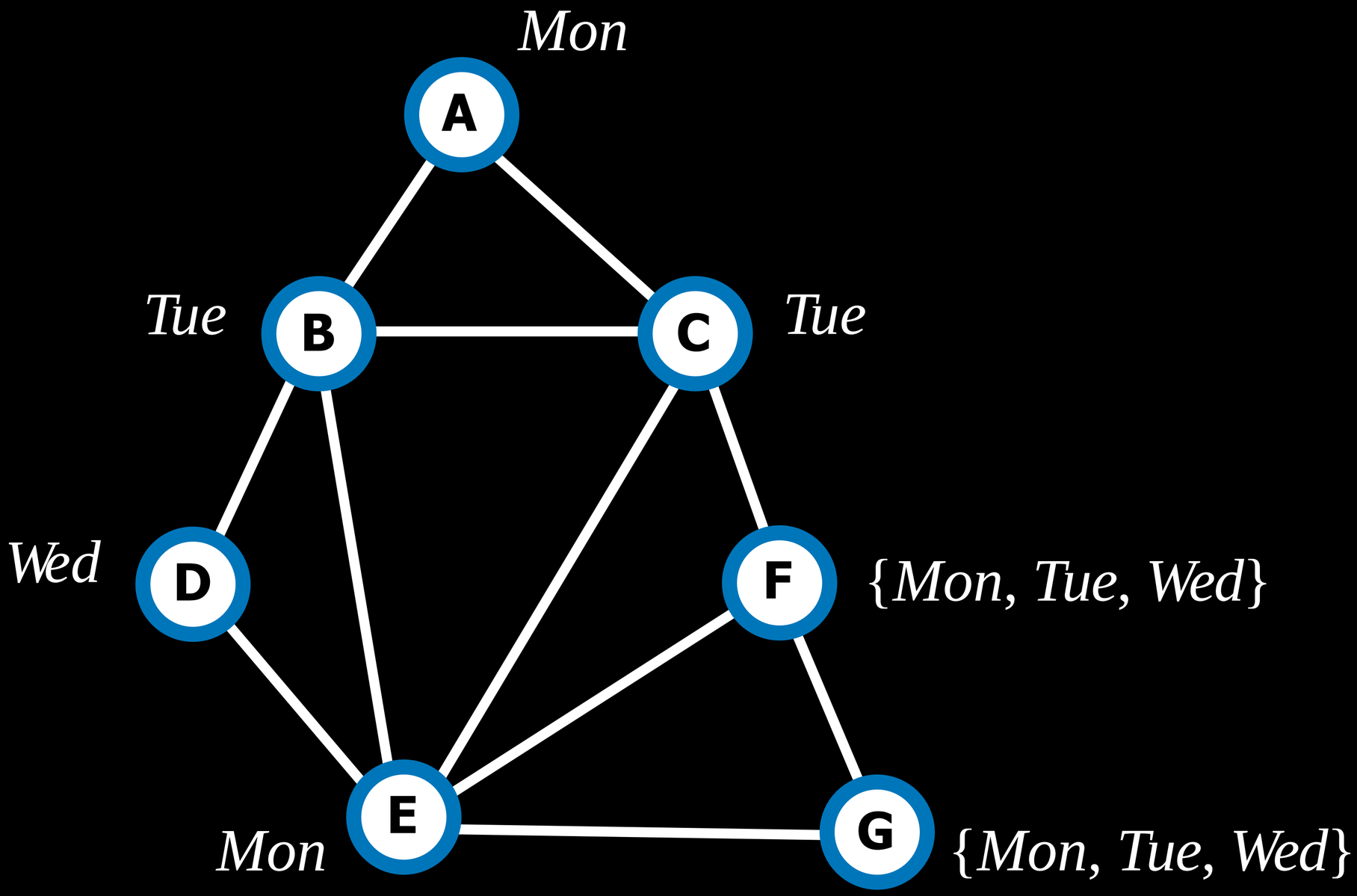

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Wed
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}

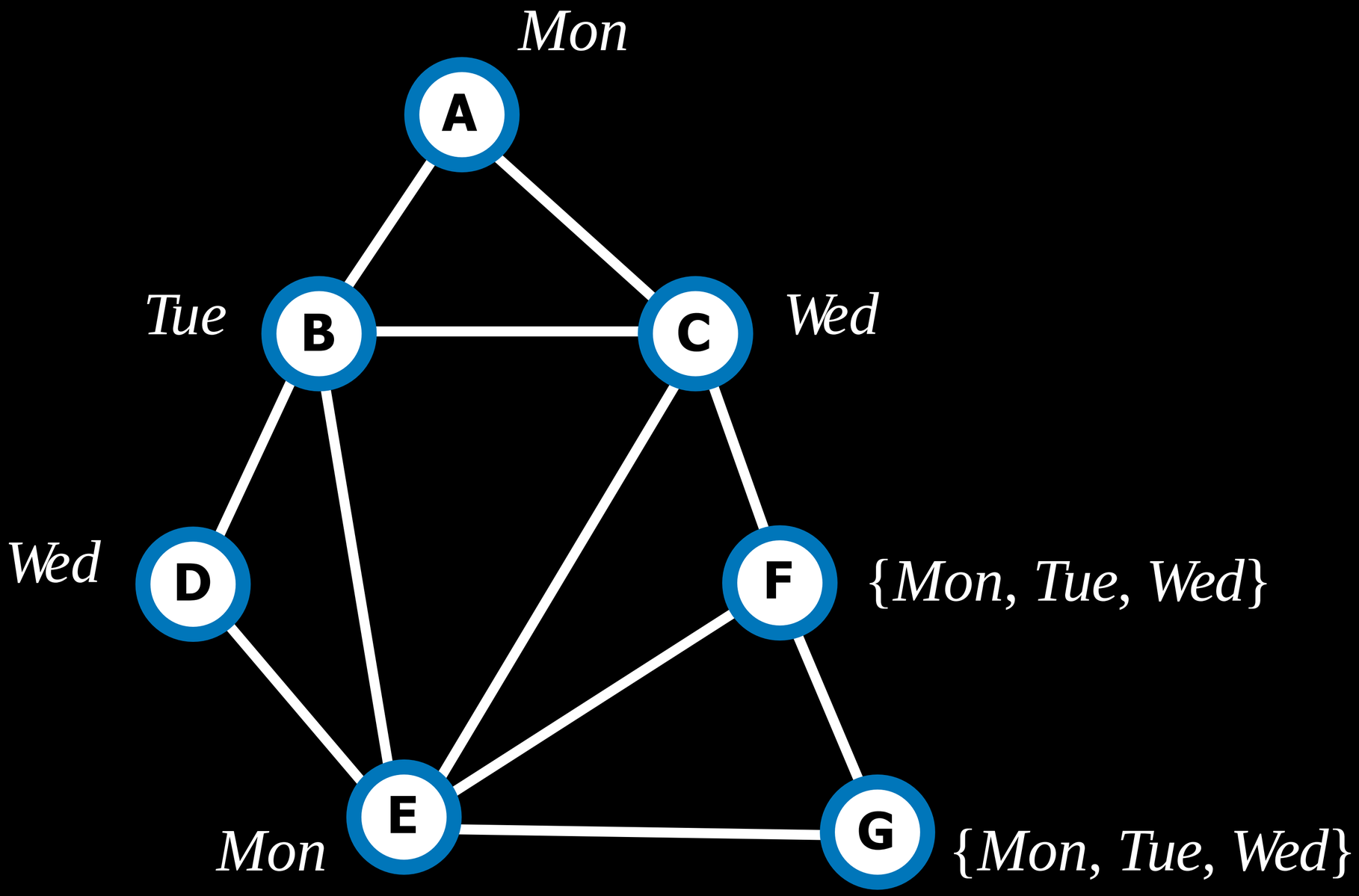

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Wed
D
F
{Mon, Tue, Wed}
Mon
E
G
{Mon, Tue, Wed}

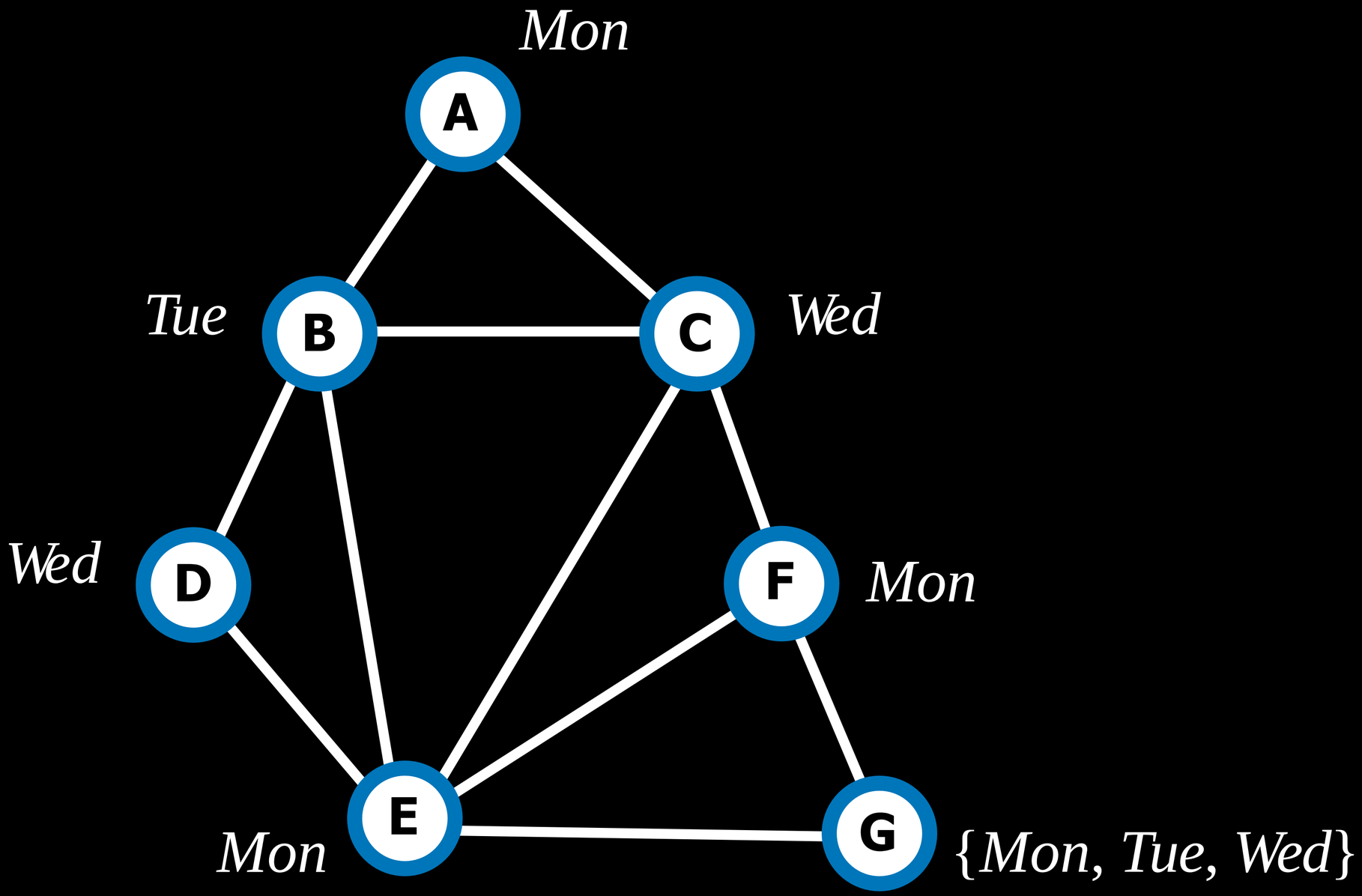

Mon
A
Tue
B
C
Mon
Wed
D
F
{Mon, Tue, Wed}
E
G
Mon
{Mon, Tue, Wed}

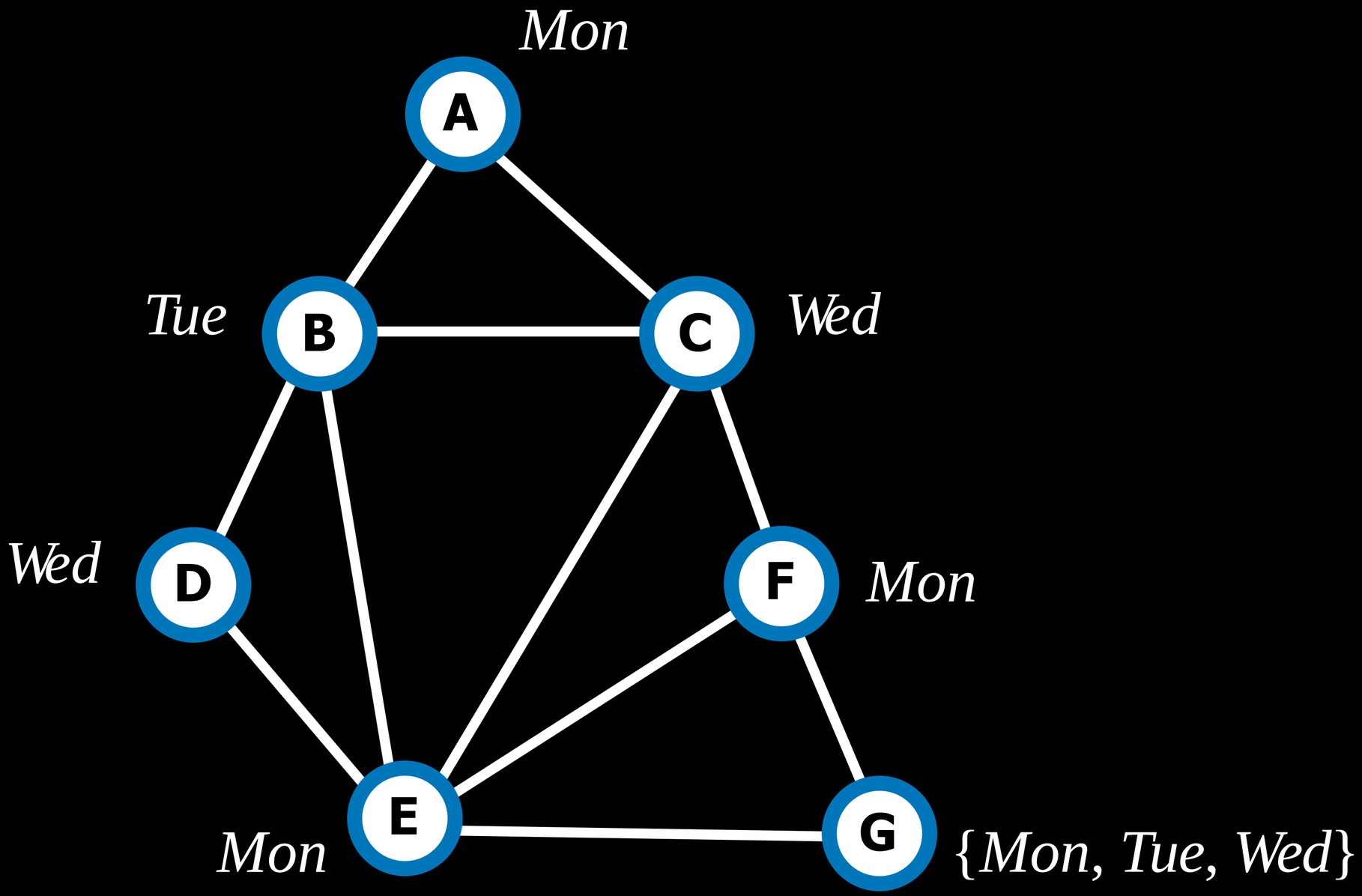

Mon
A
Tue
B
C
Mon
Wed
D
F
{Mon, Tue, Wed}
E
G
Mon
{Mon, Tue, Wed}

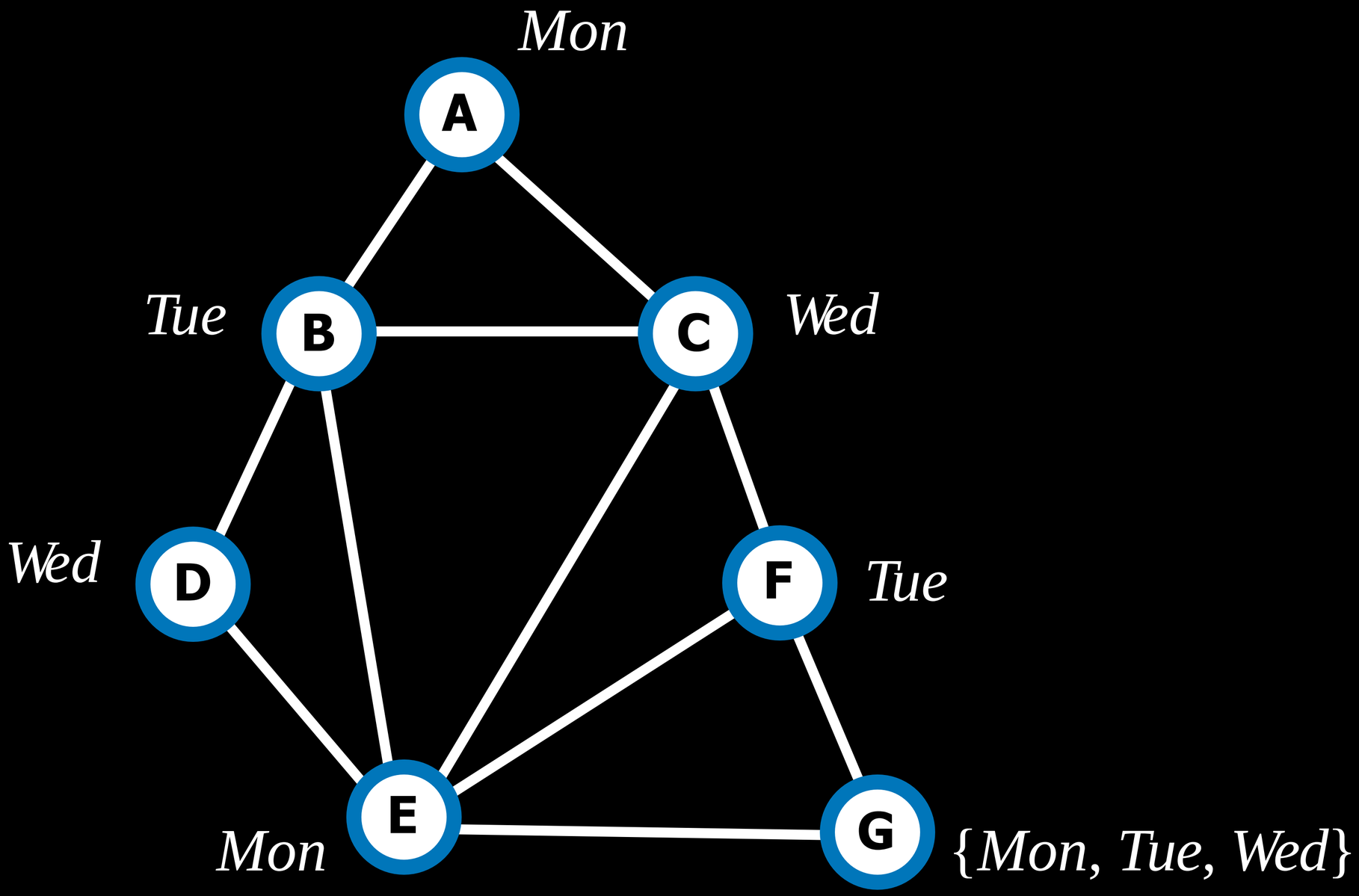

Mon
A
Tue
B
C
Tue
Wed
D
F
{Mon, Tue, Wed}
E
G
Mon
{Mon, Tue, Wed}

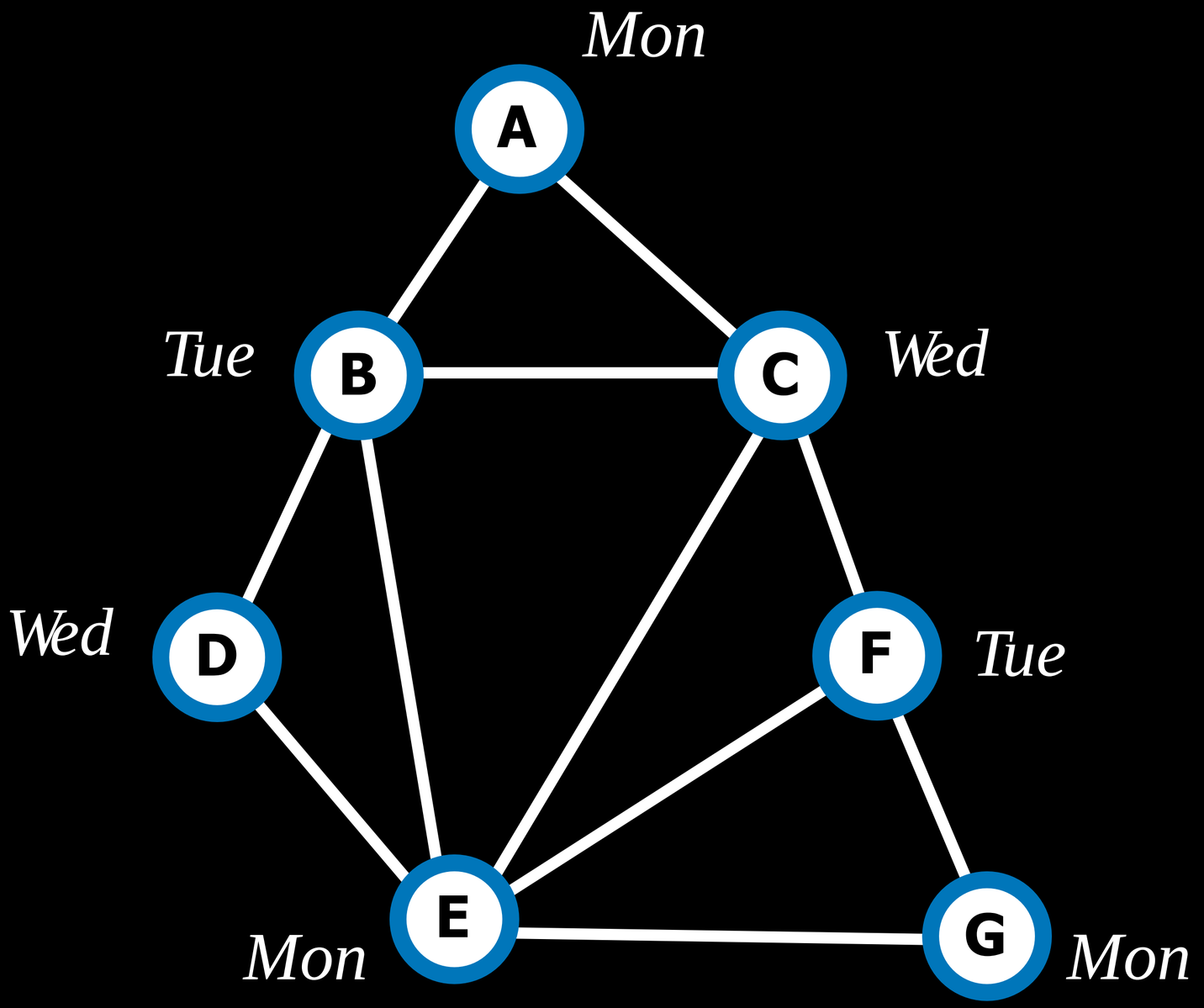

Mon
A
Tue
B
C
Tue
Wed
D
F
{Mon, Tue, Wed}
E
G
Mon
{Mon, Tue, Wed}

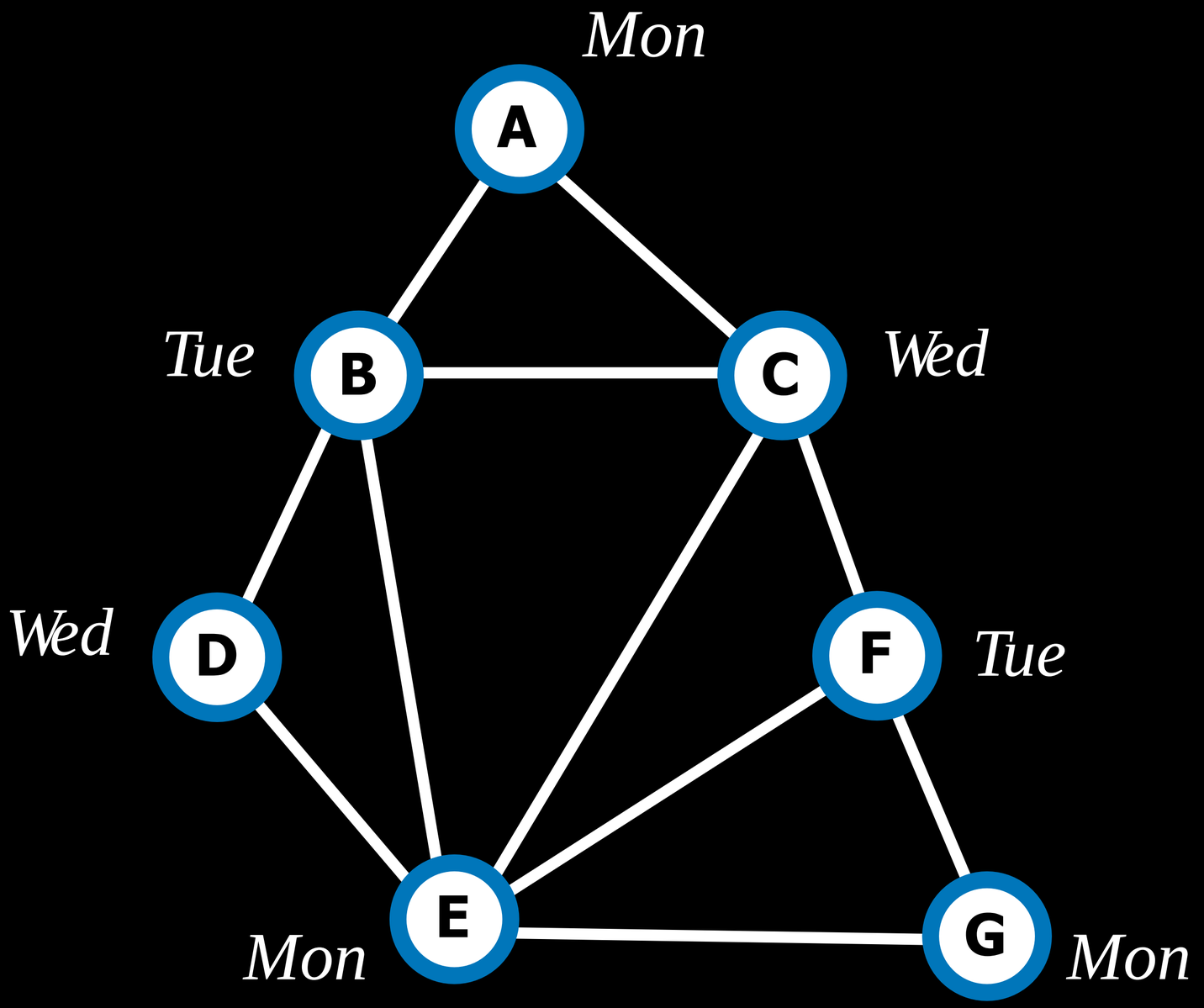

Mon
A
Tue
B
C
Wed
Wed
D
F
{Mon, Tue, Wed}
E
G
Mon
{Mon, Tue, Wed}

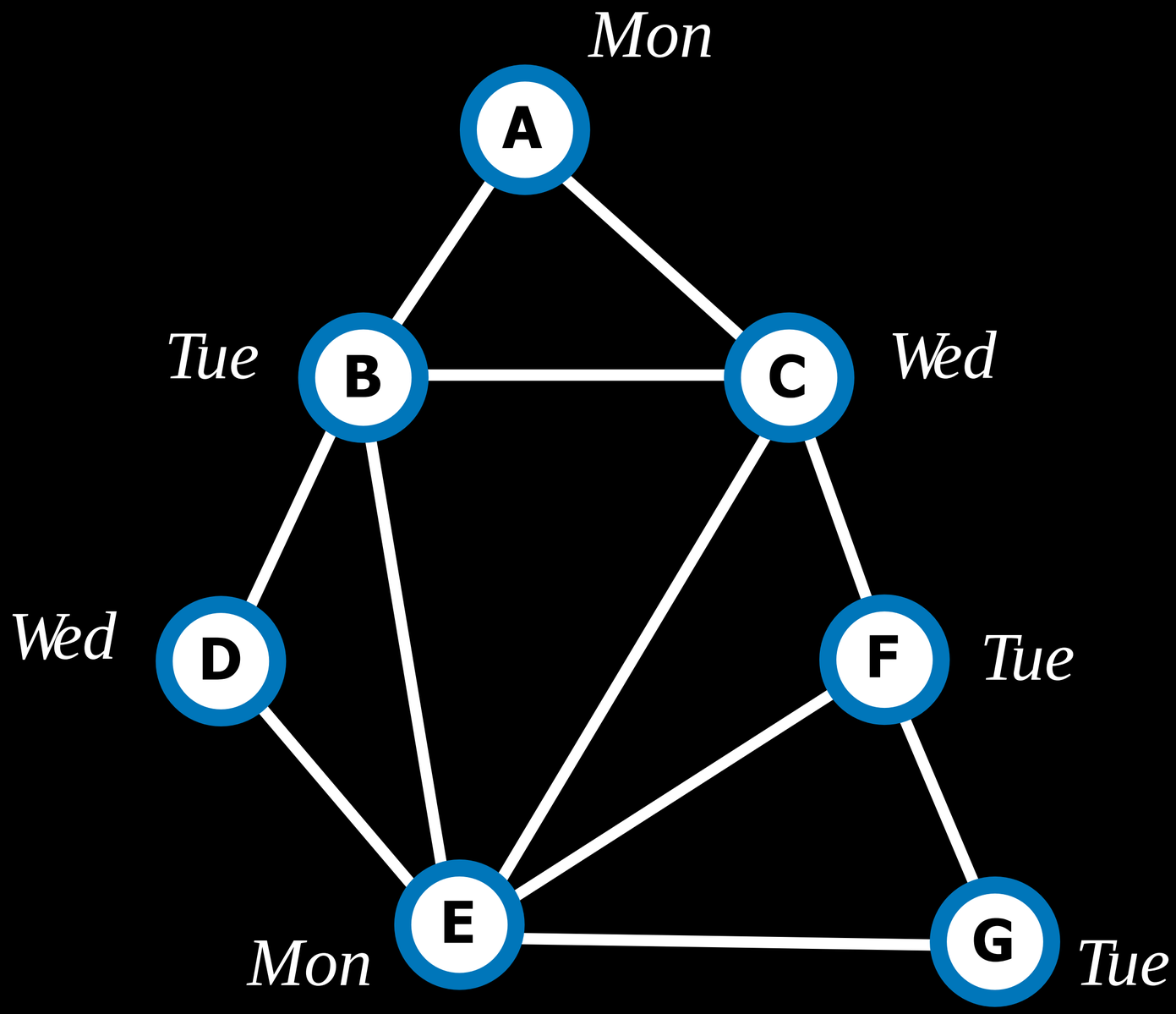

Mon
A
Tue
B
C
Wed
Wed
D
F
Mon
Mon
E
G
{Mon, Tue, Wed}

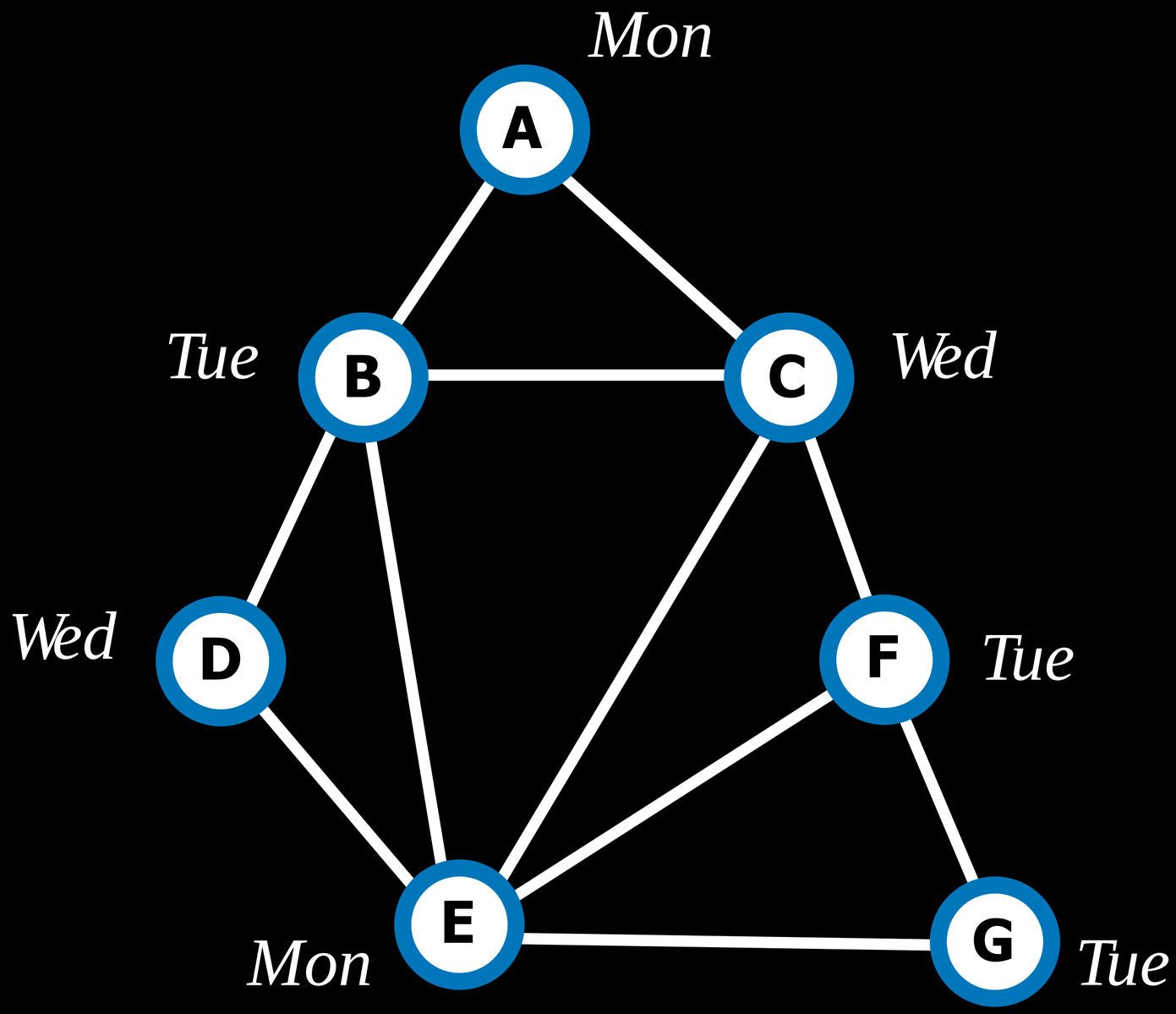

Mon
A
Tue
B
C
Wed
Wed
D
F
Mon
Mon
E
G
{Mon, Tue, Wed}

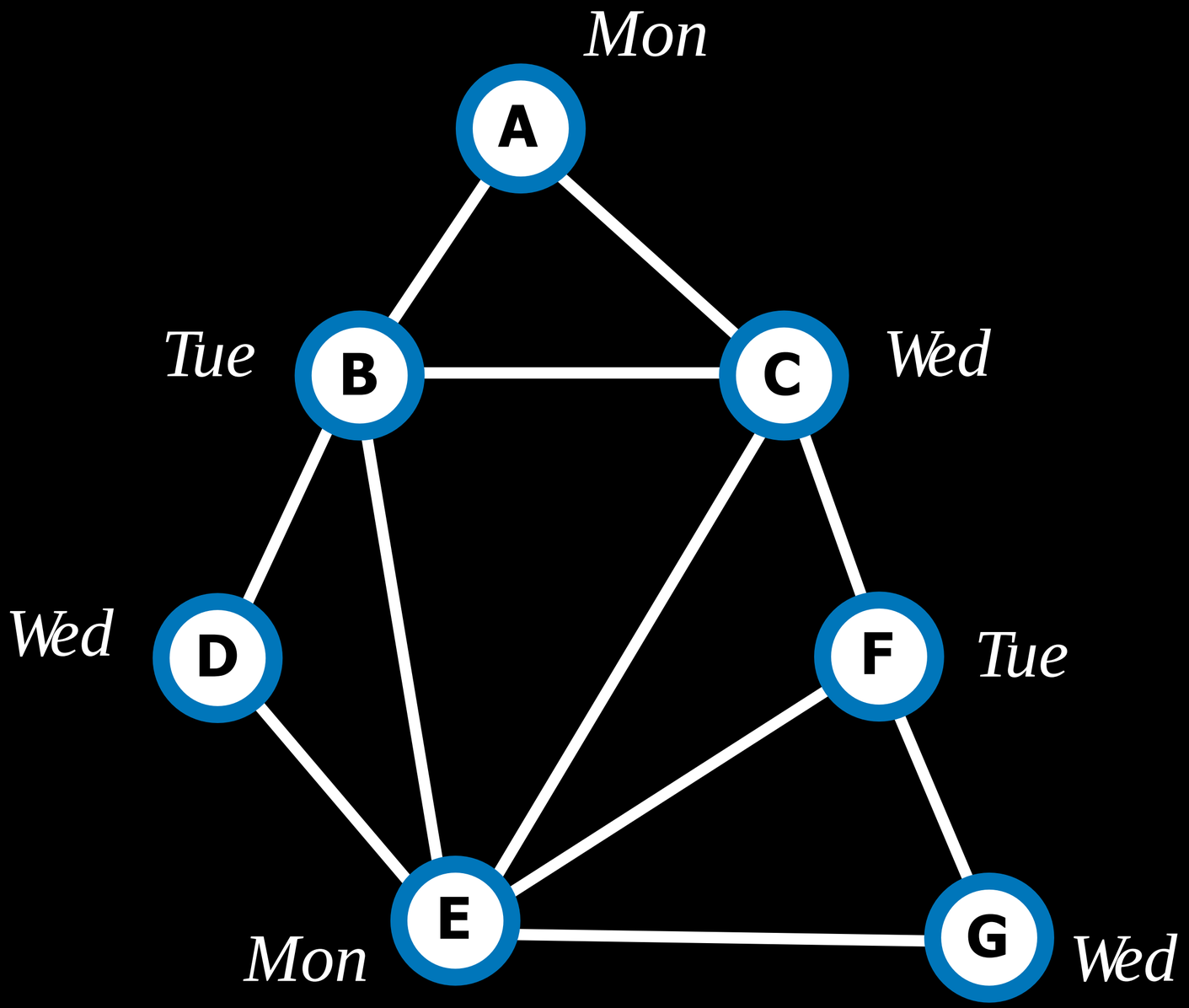

Mon
A
Tue
B
C
Wed
Wed
D
F
Tue
E
G
Mon
{Mon, Tue, Wed}


Mon
A
Tue
B
C
Wed
Wed
D
F
Tue
E
Mon
G
Mon

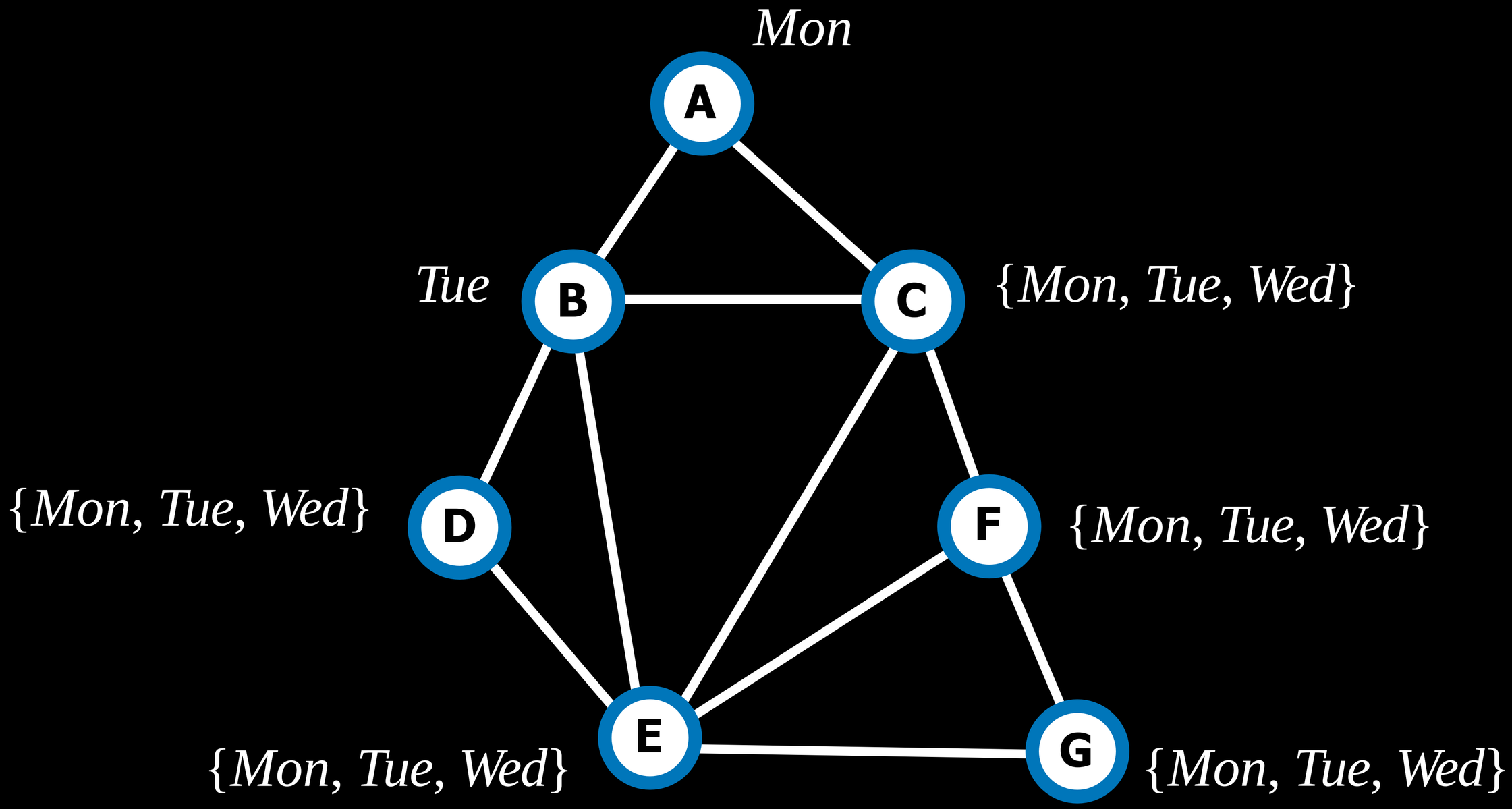

Mon
A
Tue
B
C
Wed
Wed
D
F
Tue
E
Mon
G
Mon

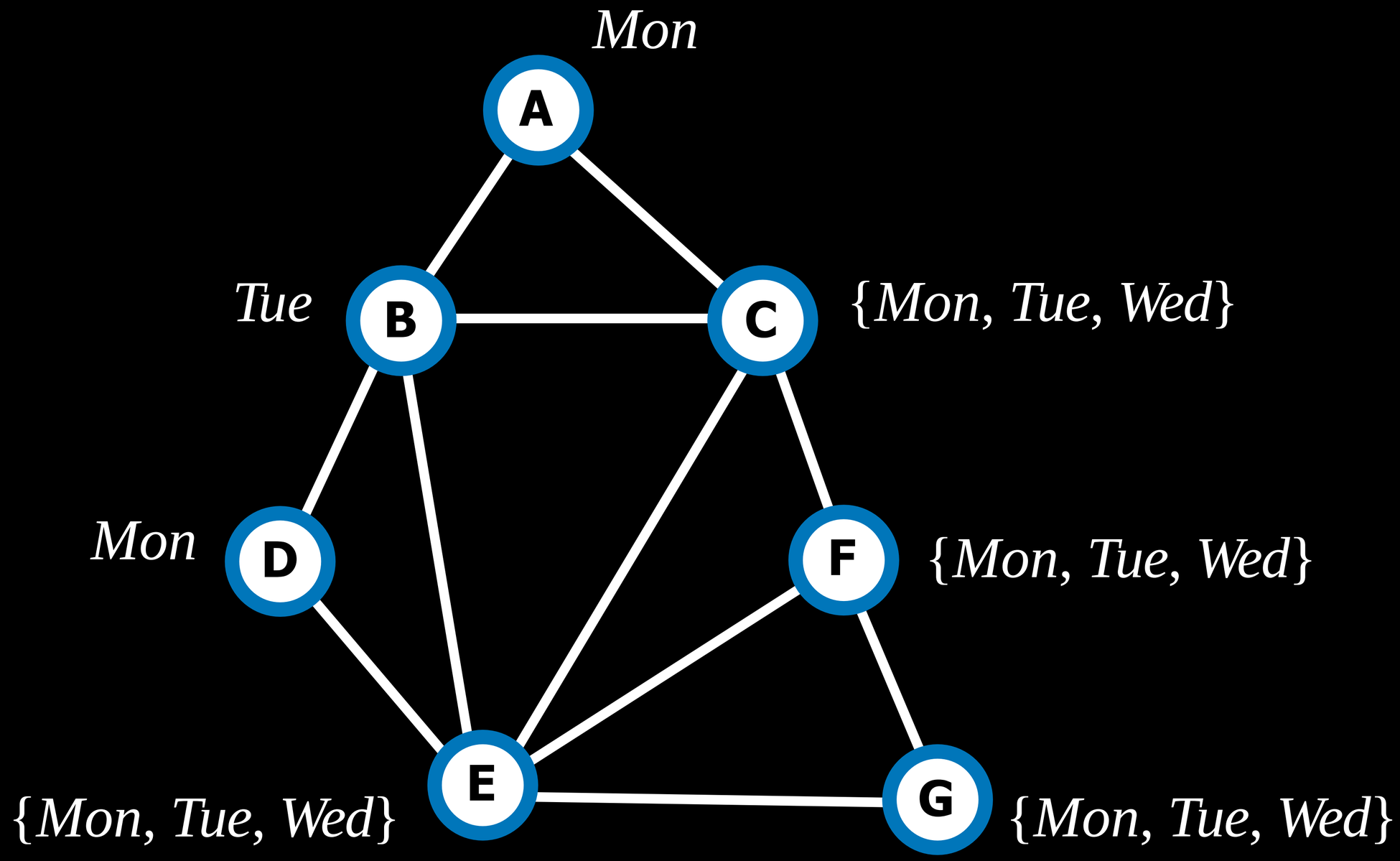

Mon
A
Tue
B
C
Wed
Wed
D
F
Tue
E
Mon
G
Tue

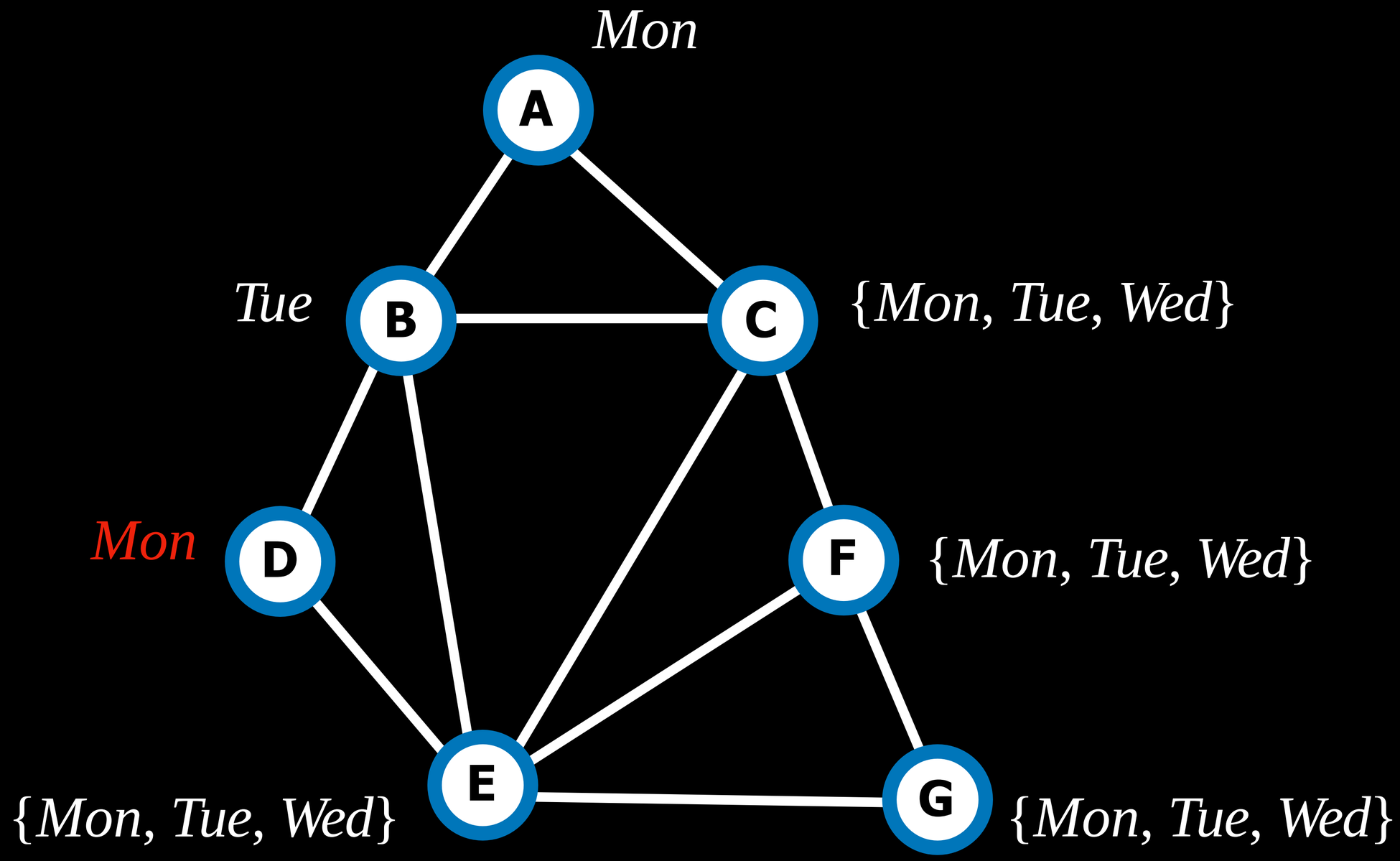

Mon
A
Tue
B
C
Wed
Wed
D
F
Tue
E
Mon
G
Tue

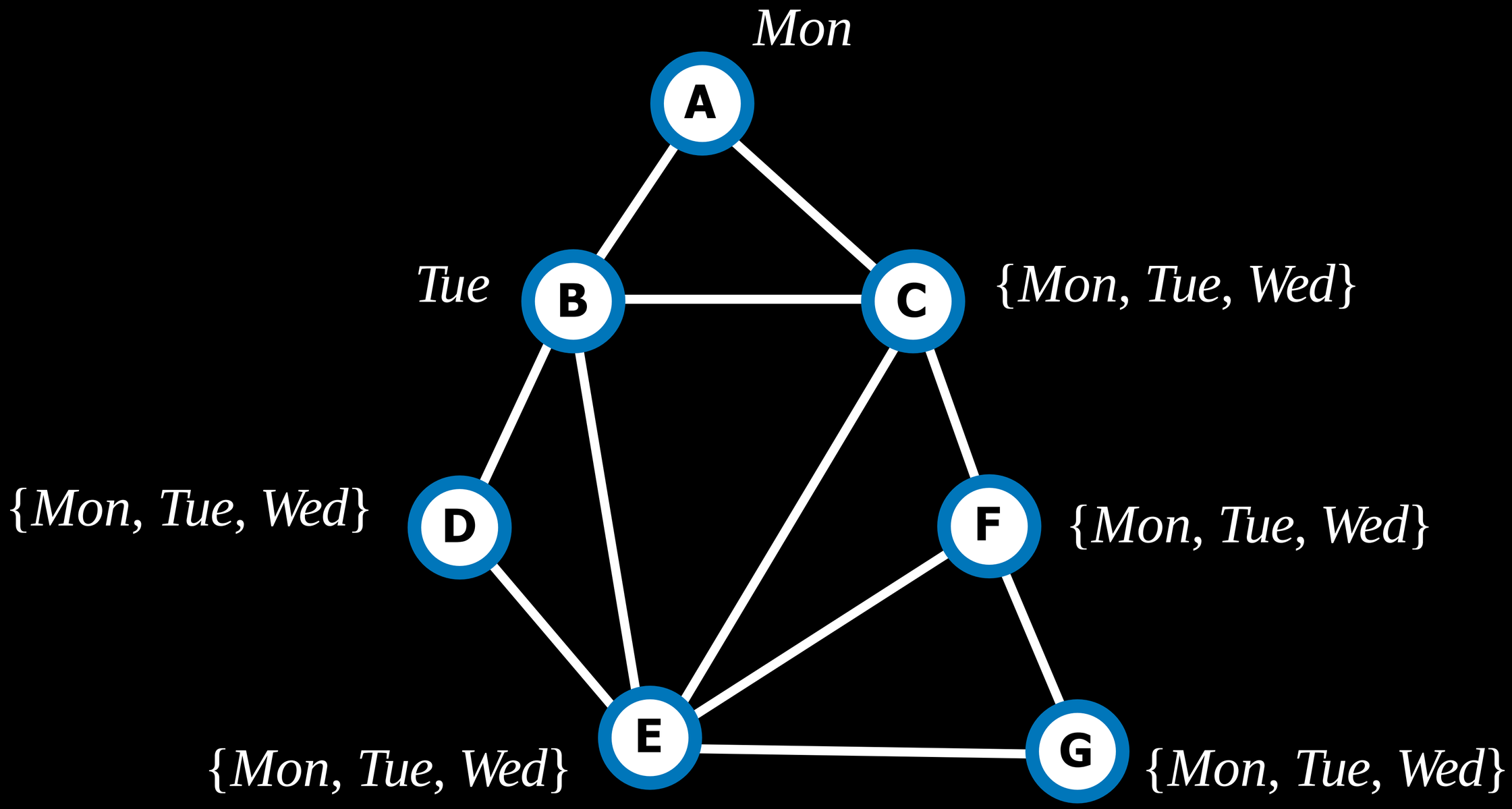

Mon
A
Tue
B
C
Wed
Wed
D
F
Tue
Mon
E
G
Wed

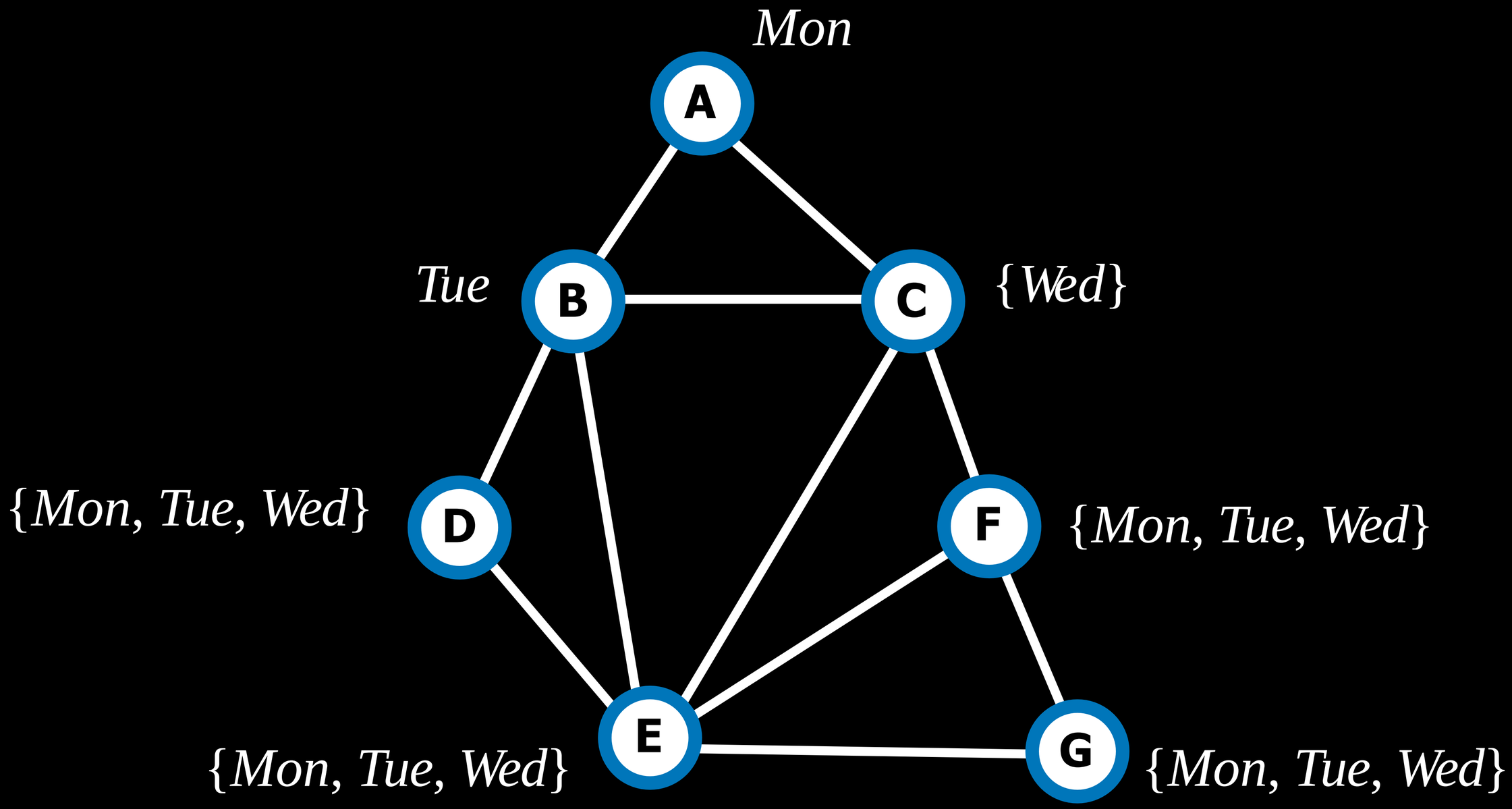
Inference

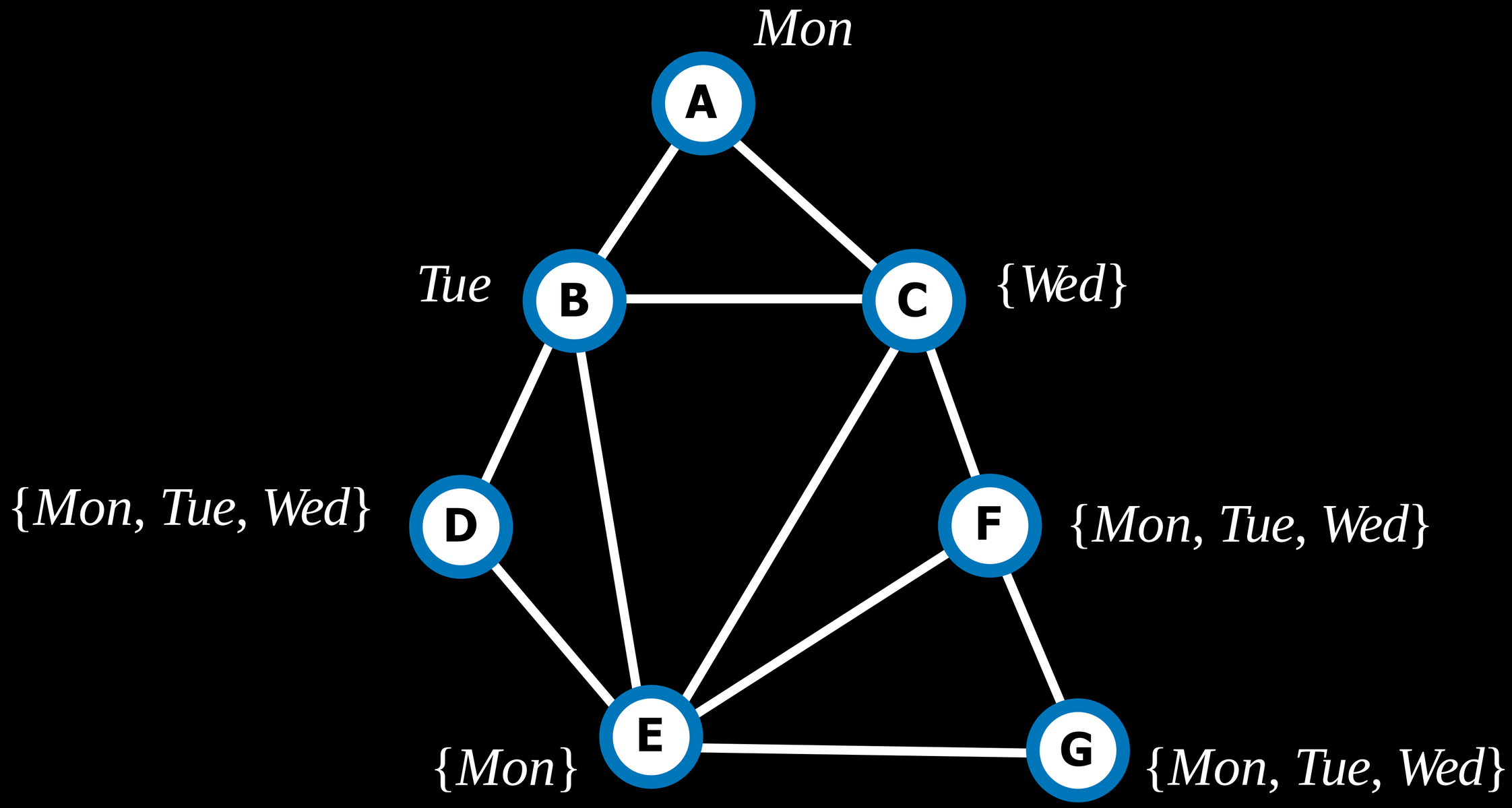

Mon
A
Tue
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

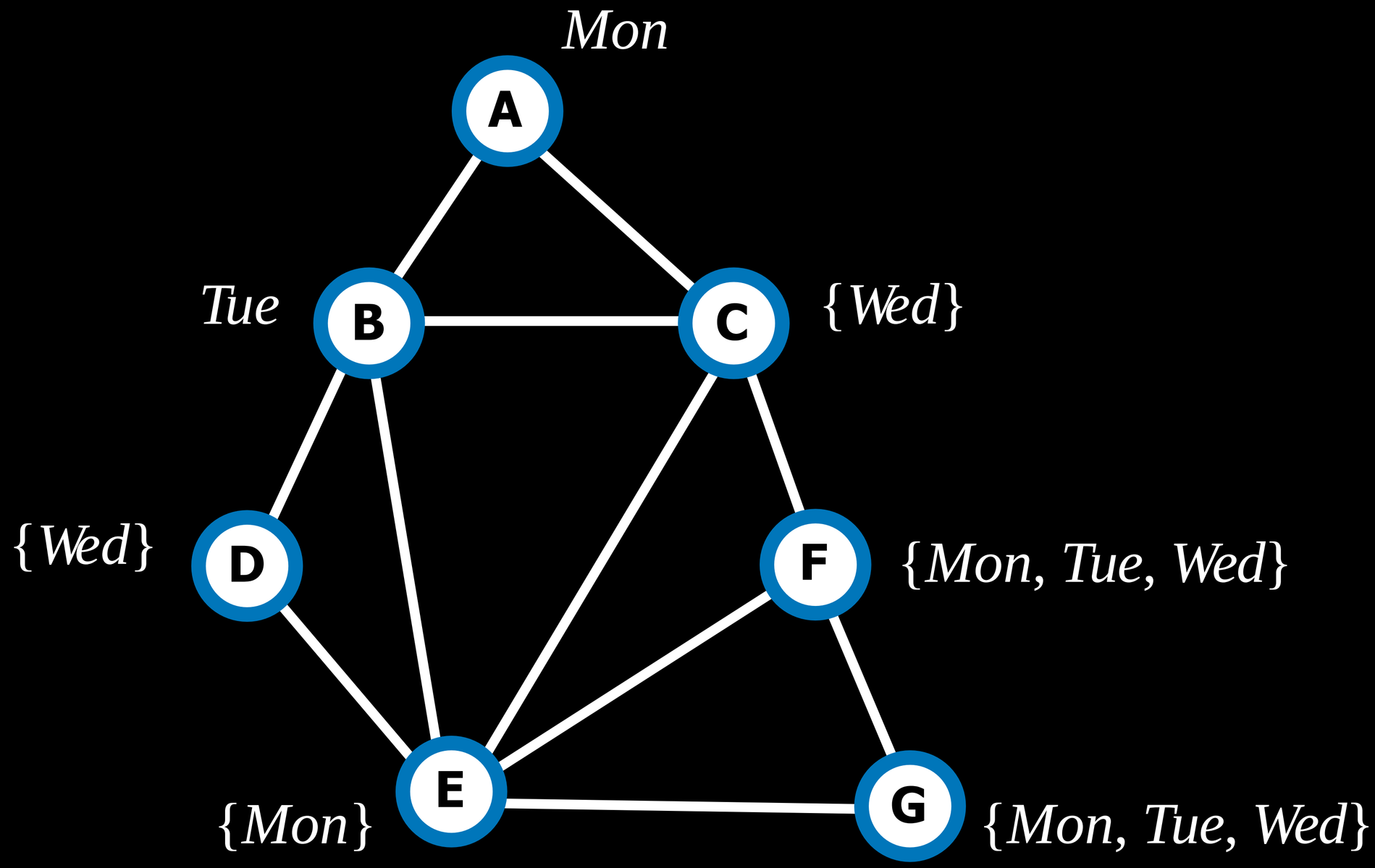

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}

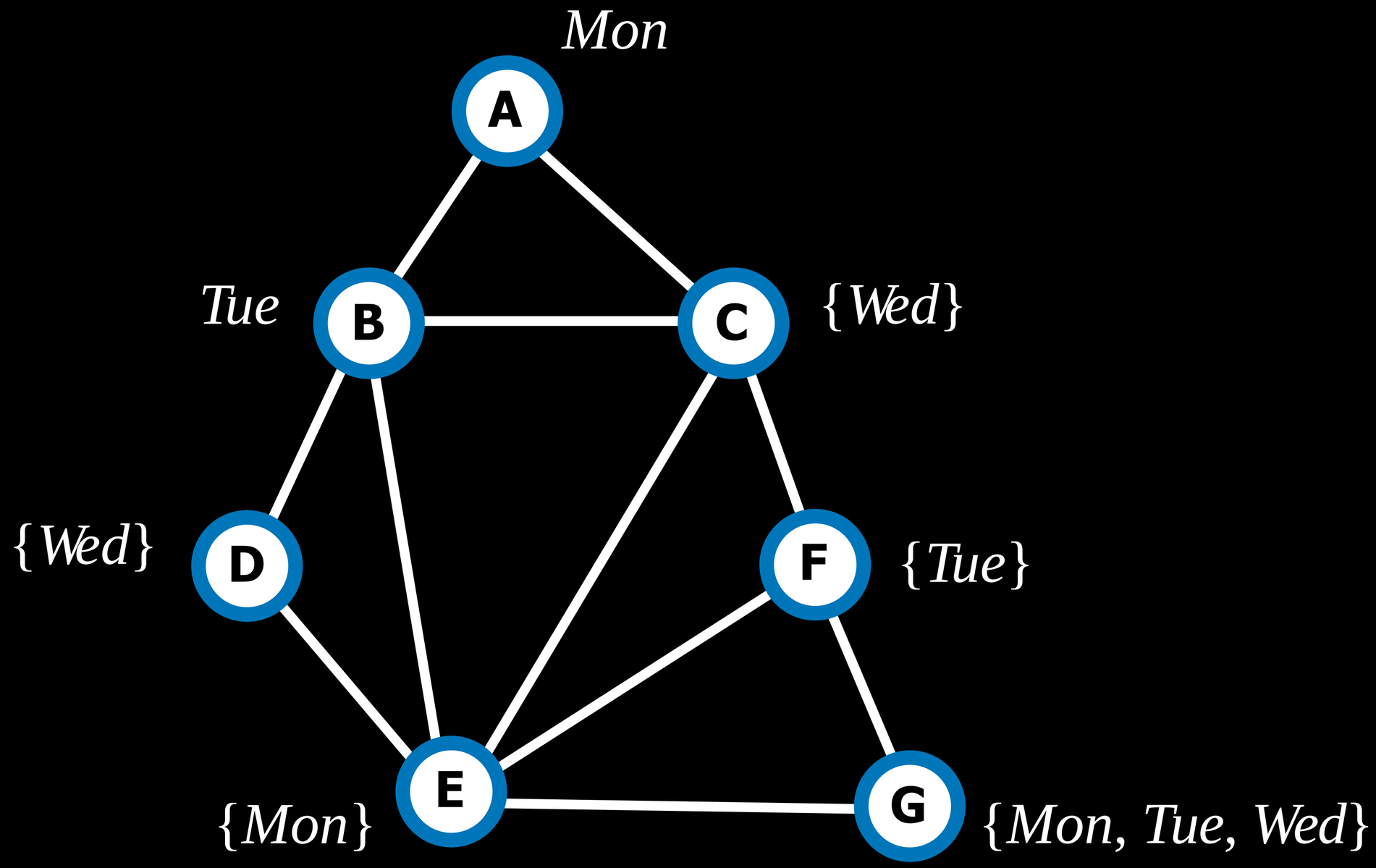

Mon
A
Tue
B
C
{Mon, Tue, Wed}
Mon
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}

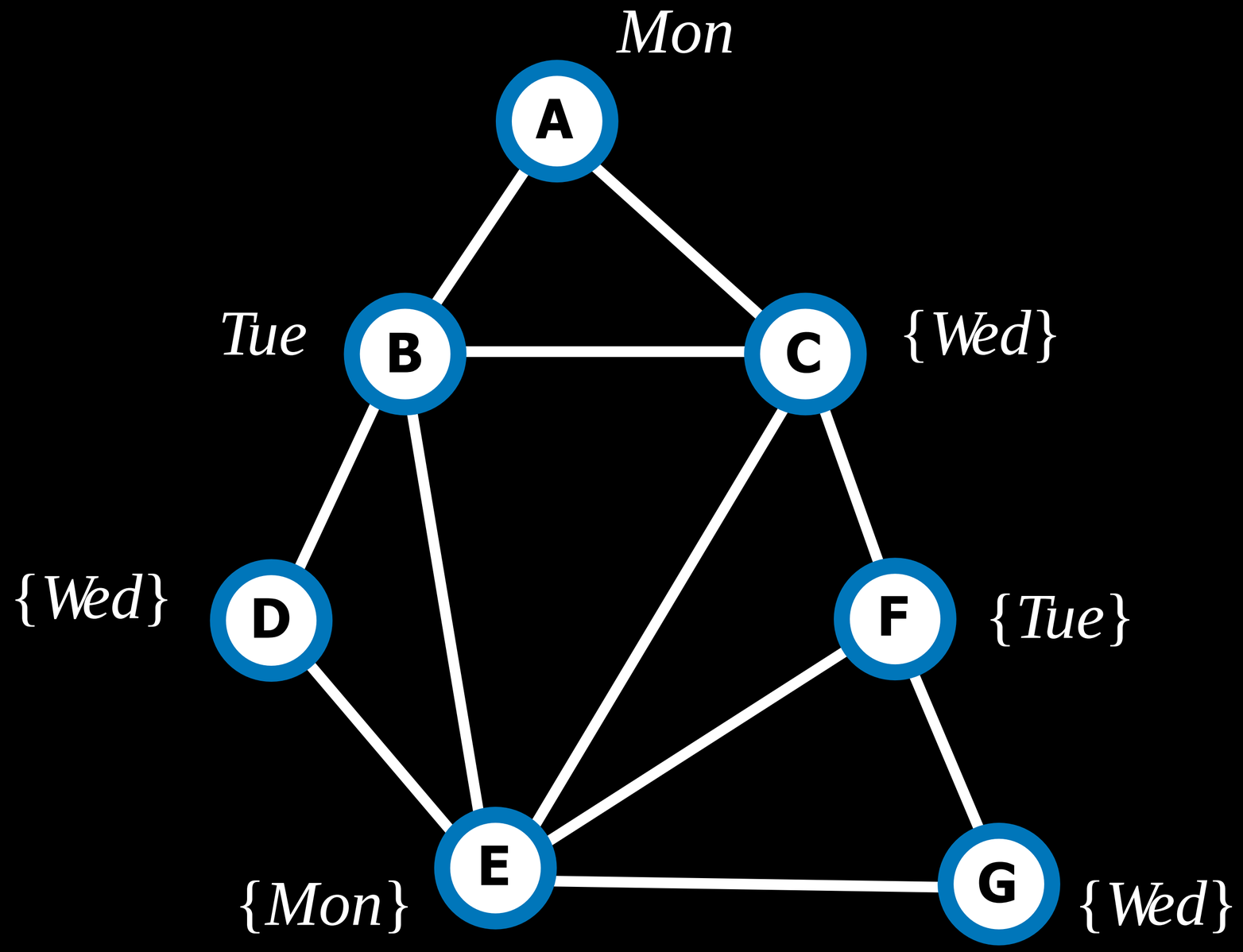

Mon
A
Tue
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

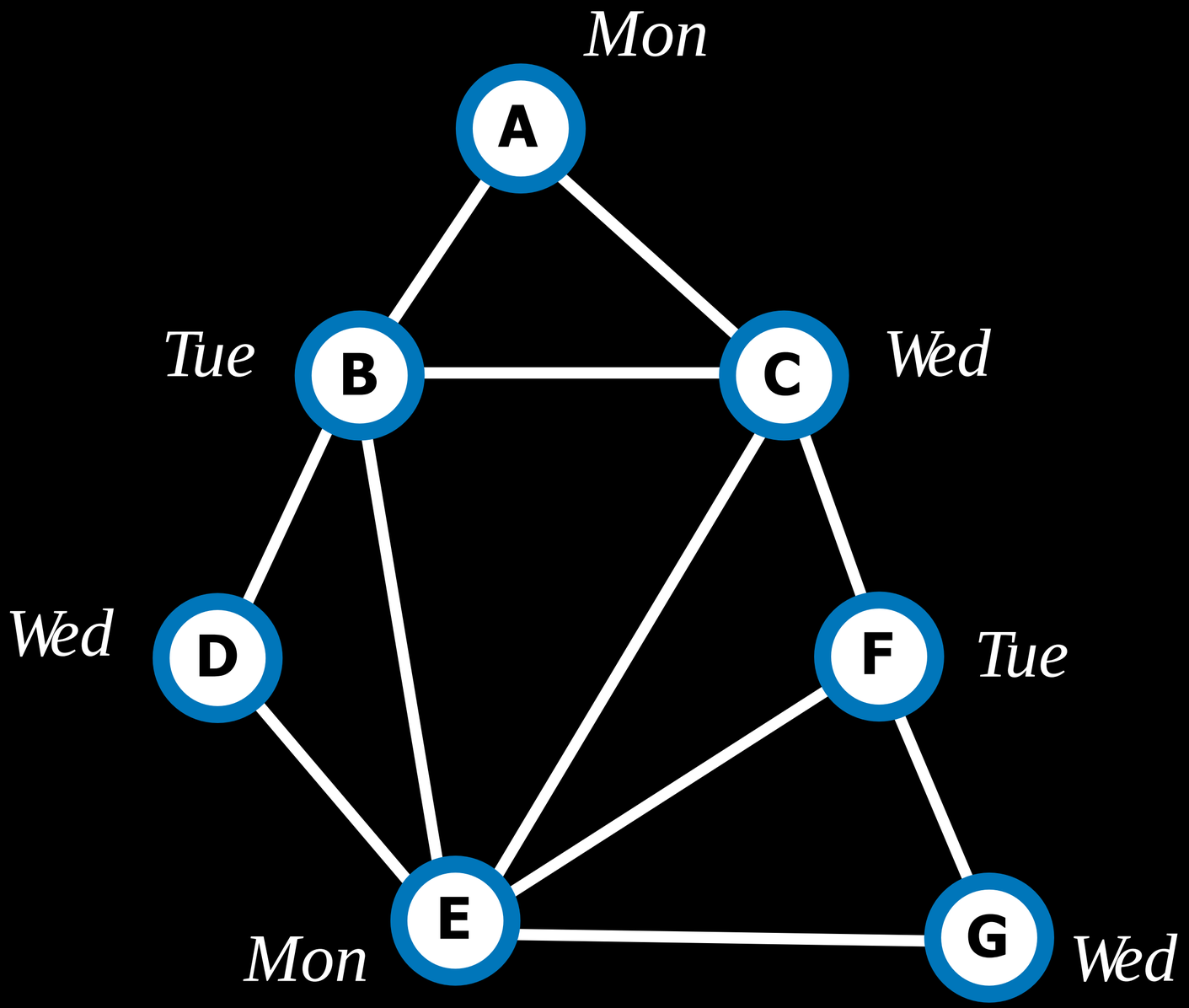

Mon
A
Tue
B
C
{Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}


Mon
A
Tue
B
C
{Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
{Mon}
E
G
{Mon, Tue, Wed}


Mon
A
Tue
B
C
{Wed}
{Wed}
D
F
{Mon, Tue, Wed}
{Mon}
E
G
{Mon, Tue, Wed}


Mon
A
Tue
B
C
{Wed}
{Wed}
D
F
{Tue}
E
G
{Mon}
{Mon, Tue, Wed}


Mon
A
Tue
B
C
{Wed}
{Wed}
D
F
{Tue}
E
G
{Mon}
{Wed}


Mon
A
Tue
B
C
Wed
Wed
D
F
Tue
Mon
E
G
Wed

maintaining arc-consistency

algorithm for enforcing arc-consistency every time we make a new assignment

maintaining arc-consistency

When we make a new assignment to X, calls AC-3, starting with a queue of all arcs (Y, X) where Y is a neighbor of X

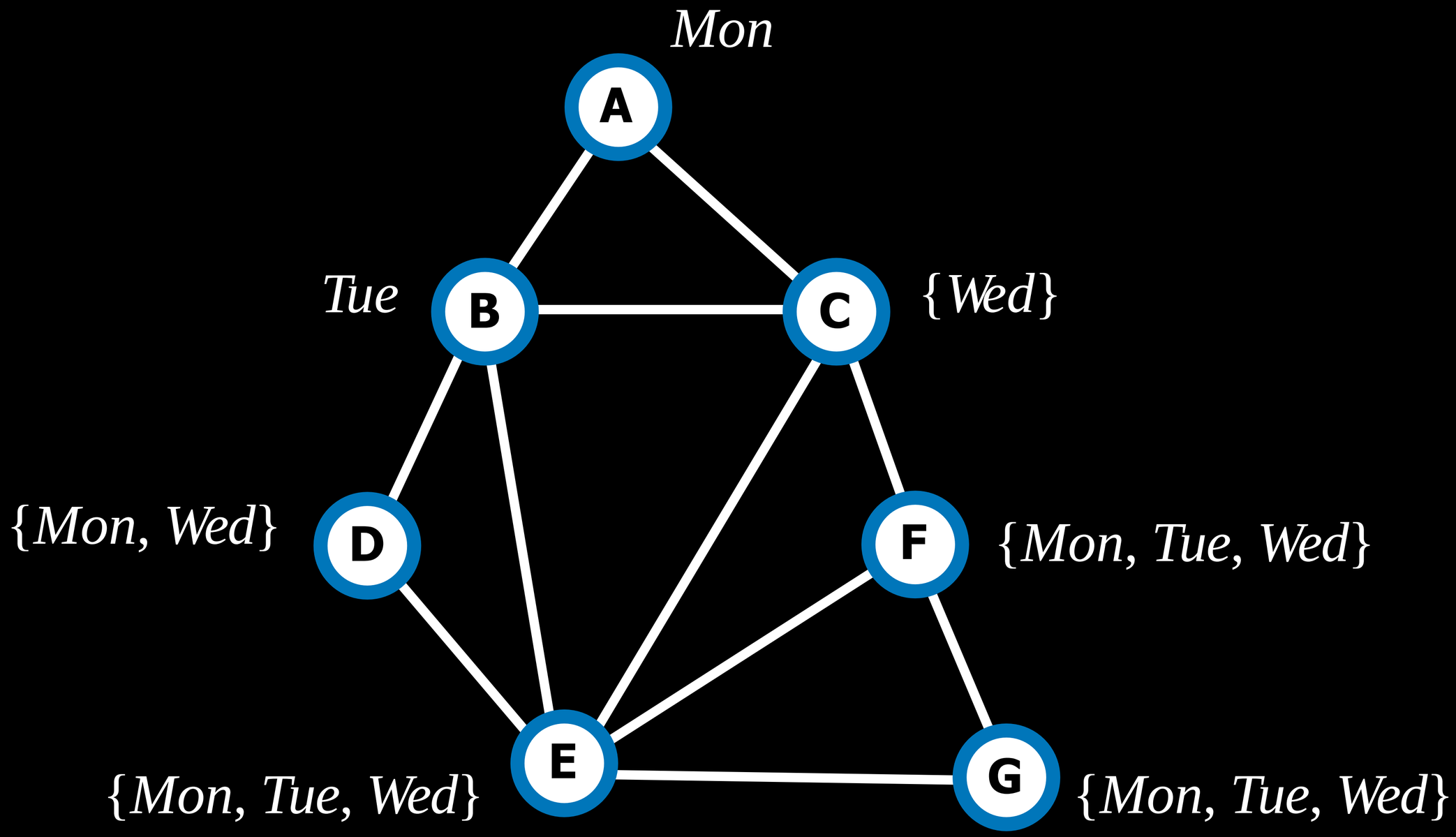
```
function BACKTRACK(assignment, csp):
    if assignment complete: return assignment
    var = SELECT-UNASSIGNED-VAR(assignment, csp)
    for value in DOMAIN-VALUES(var, assignment, csp):
        if value consistent with assignment:
            add {var = value} to assignment
            inferences = INFERENCE(assignment, csp)
            if inferences ≠ failure: add inferences to assignment
            result = BACKTRACK(assignment, csp)
            if result ≠ failure: return result
        remove {var = value} and inferences from assignment
    return failure
```

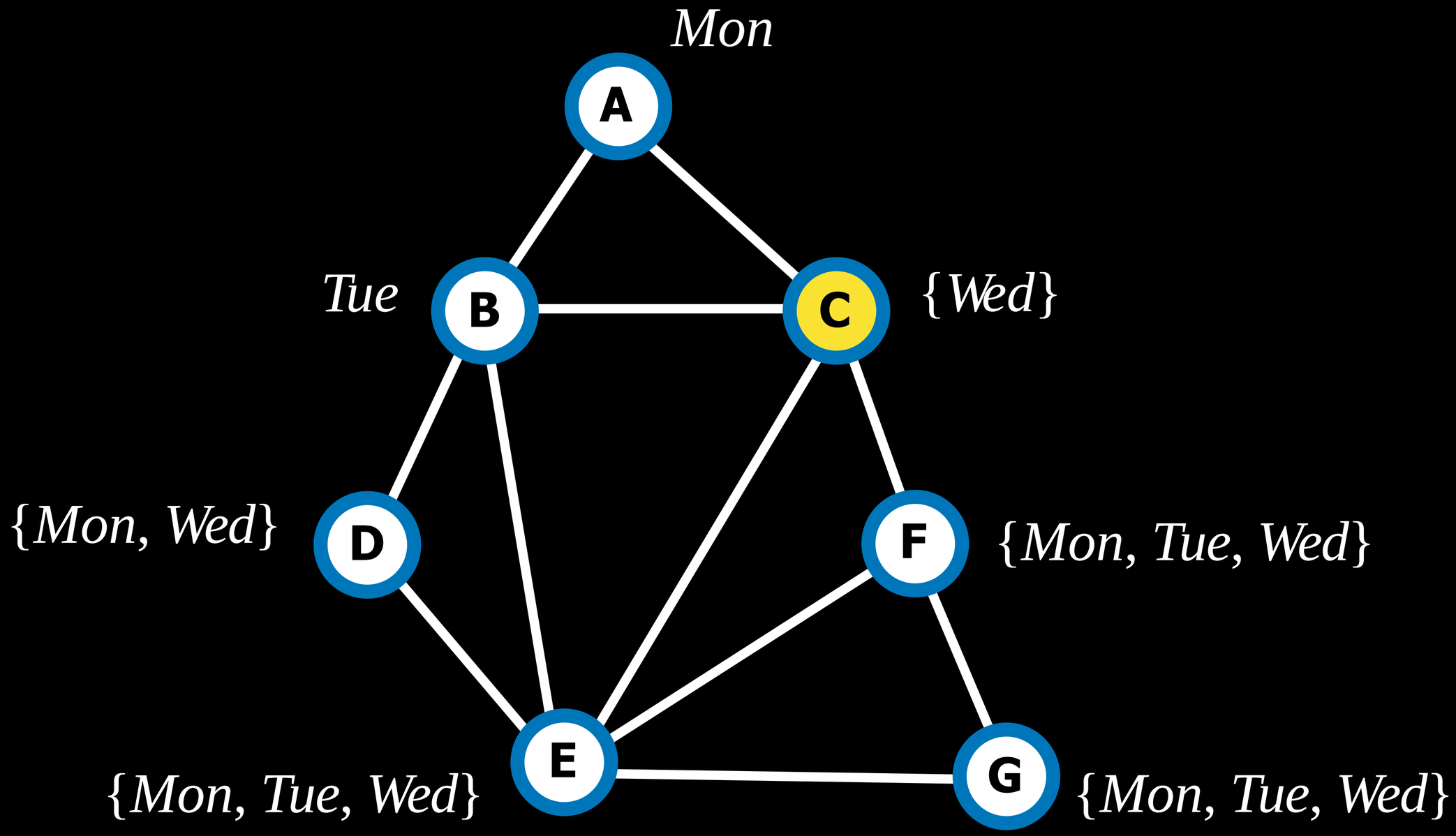
```
function BACKTRACK(assignment, csp):
    if assignment complete: return assignment
    var = SELECT-UNASSIGNED-VAR(assignment, csp)
    for value in DOMAIN-VALUES(var, assignment, csp):
        if value consistent with assignment:
            add {var = value} to assignment
            inferences = INFERENCE(assignment, csp)
            if inferences ≠ failure: add inferences to assignment
            result = BACKTRACK(assignment, csp)
            if result ≠ failure: return result
        remove {var = value} and inferences from assignment
    return failure
```

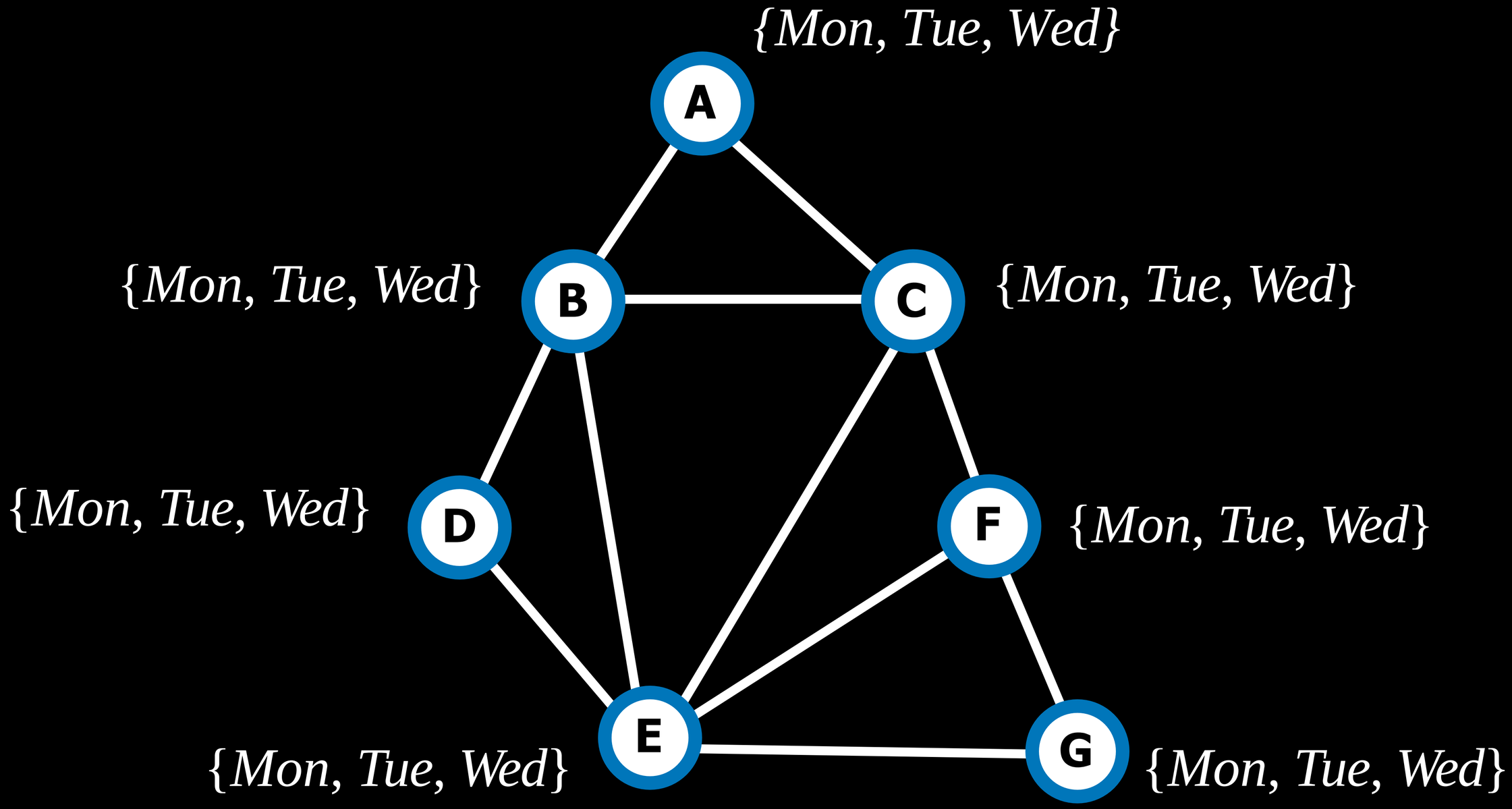
```
function BACKTRACK(assignment, csp):
    if assignment complete: return assignment
    var = SELECT-UNASSIGNED-VAR(assignment, csp)
    for value in DOMAIN-VALUES(var, assignment, csp):
        if value consistent with assignment:
            add {var = value} to assignment
            inferences = INFERENCE(assignment, csp)
            if inferences ≠ failure: add inferences to assignment
            result = BACKTRACK(assignment, csp)
            if result ≠ failure: return result
        remove {var = value} and inferences from assignment
    return failure
```

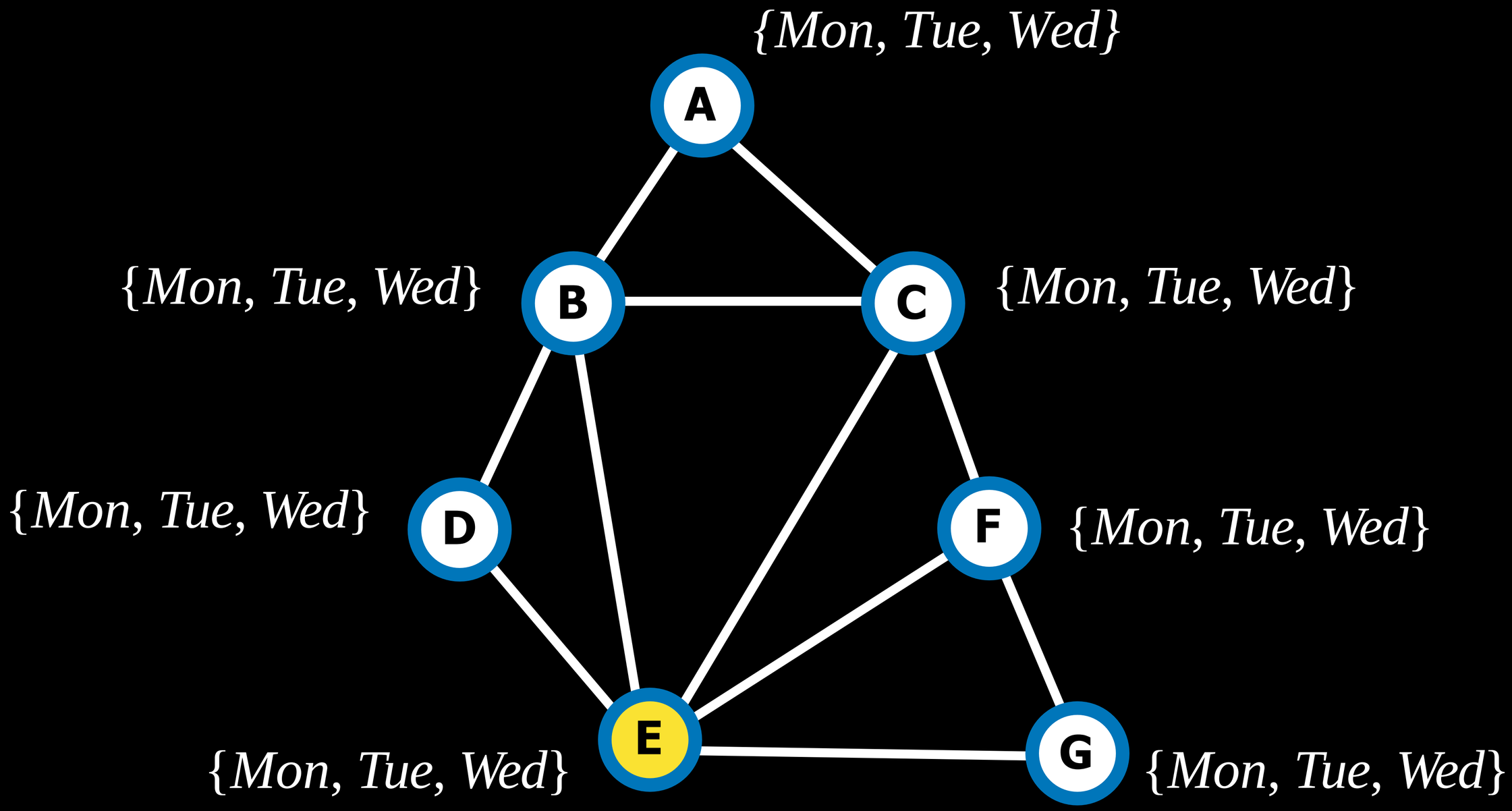
Select-Unassigned-Var

- **minimum remaining values (MRV)** heuristic: select the variable that has the smallest domain
- **degree** heuristic: select the variable that has the highest degree


Mon
A
Tue
B
C
{Wed}
{Mon, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}
{Mon, Tue, Wed}


Mon
A
Tue
B
C
{Wed}
{Mon, Wed}
D
F
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}


{Mon, Tue, Wed}
A
{Mon, Tue, Wed}
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

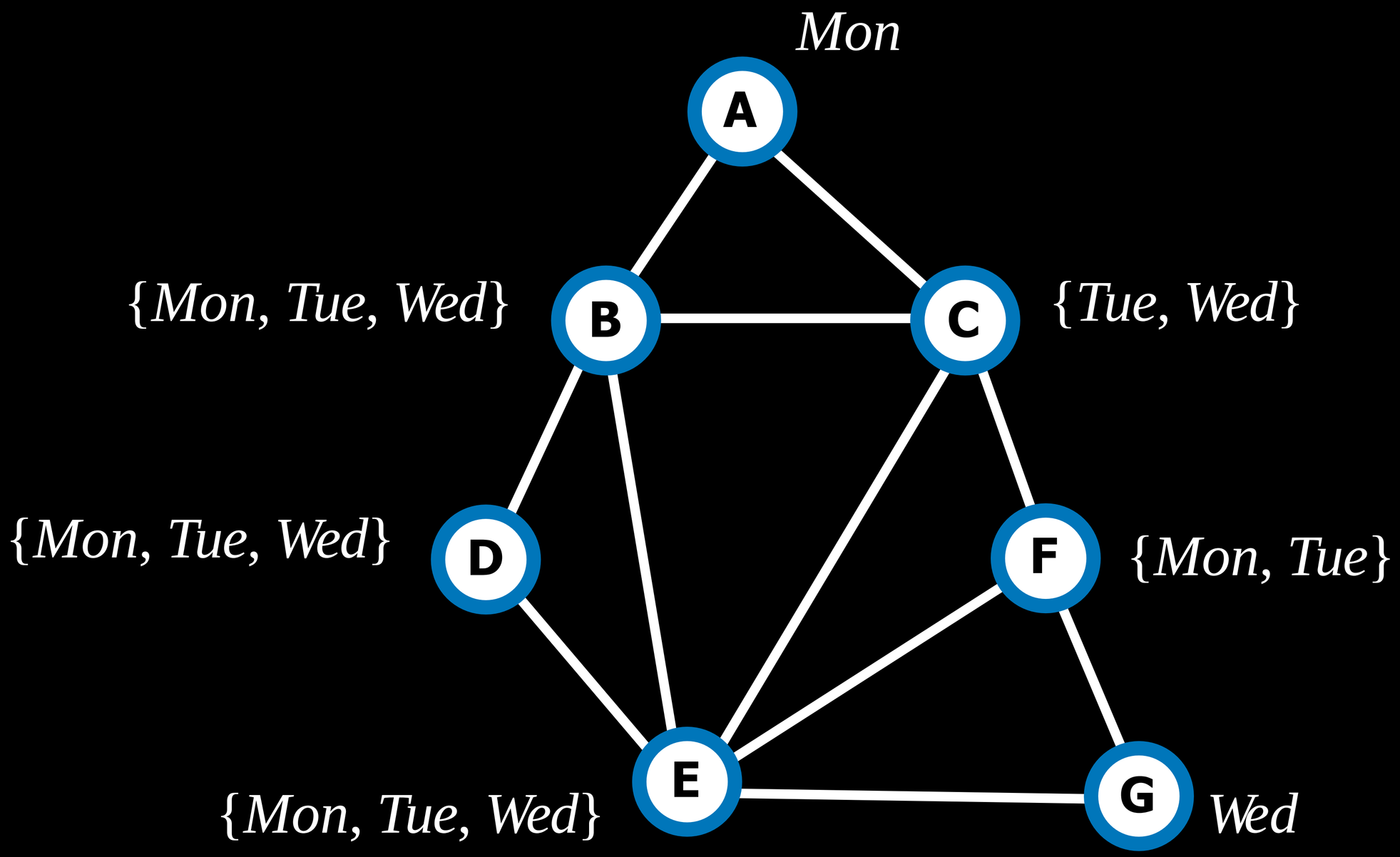

{Mon, Tue, Wed}
A
{Mon, Tue, Wed}
B
C
{Mon, Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue, Wed}
{Mon, Tue, Wed}
E
G
{Mon, Tue, Wed}

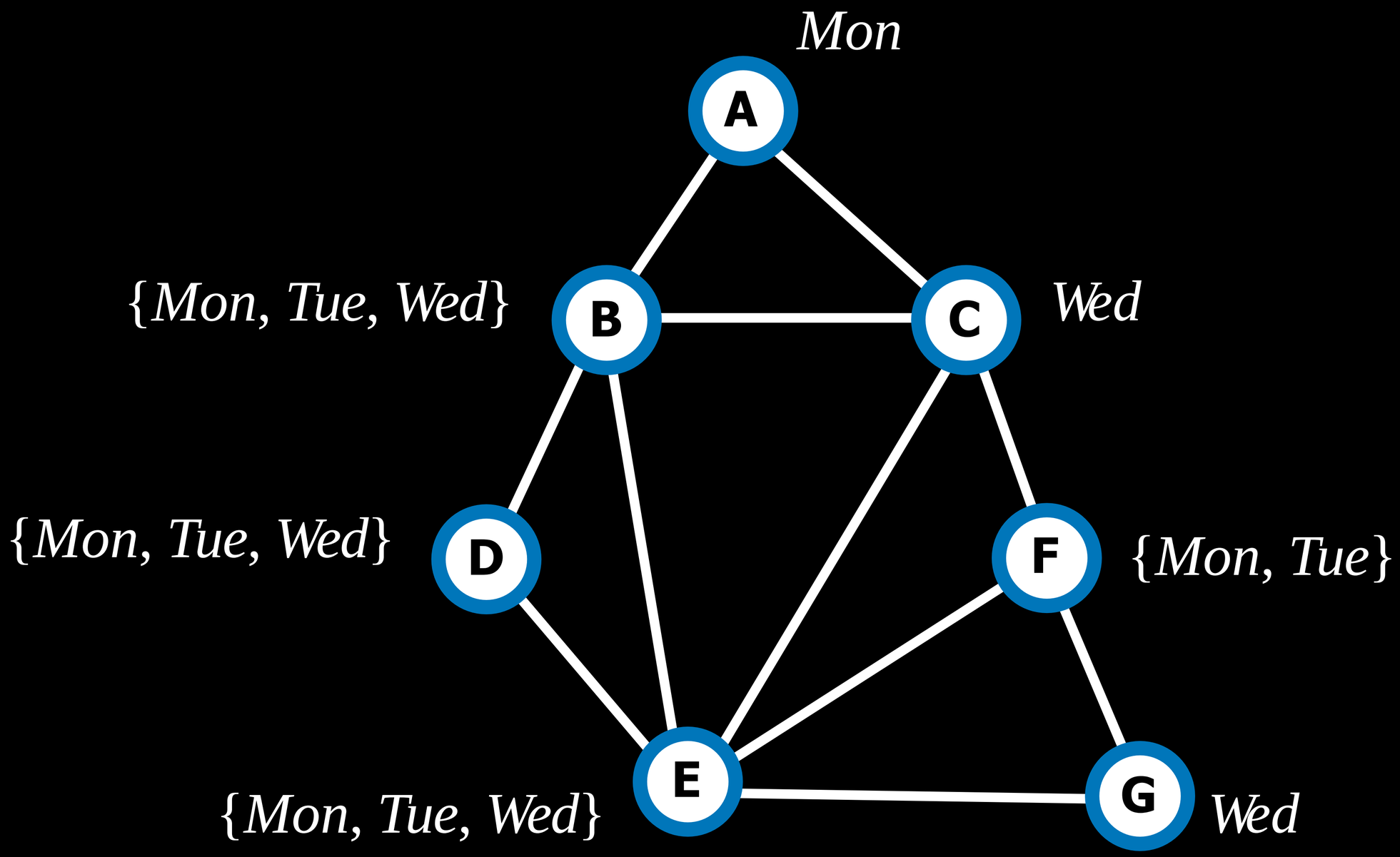
```
function BACKTRACK(assignment, csp):
    if assignment complete: return assignment
    var = SELECT-UNASSIGNED-VAR(assignment, csp)
    for value in DOMAIN-VALUES(var, assignment, csp):
        if value consistent with assignment:
            add {var = value} to assignment
            inferences = INFERENCE(assignment, csp)
            if inferences ≠ failure: add inferences to assignment
            result = BACKTRACK(assignment, csp)
            if result ≠ failure: return result
        remove {var = value} and inferences from assignment
    return failure
```

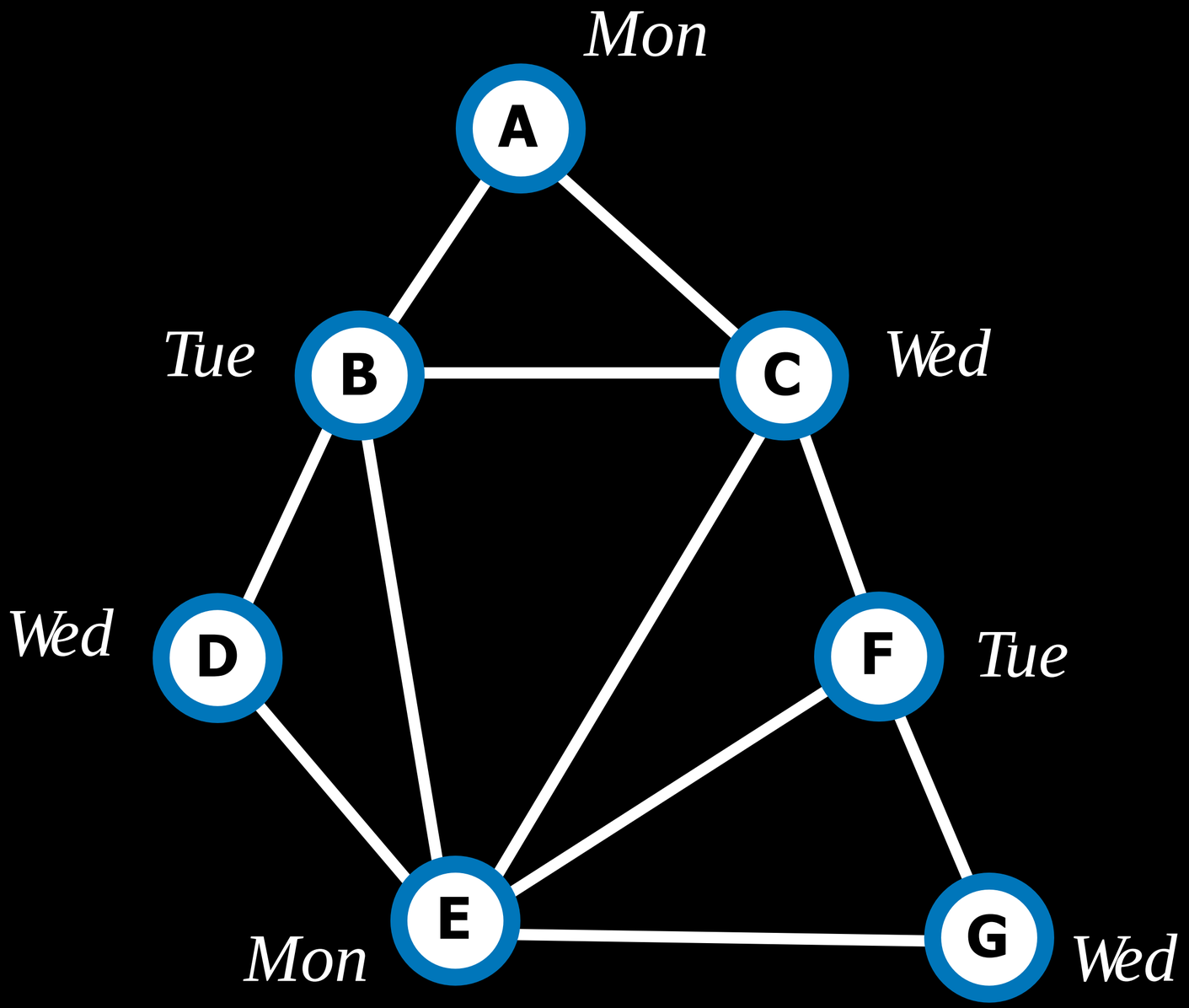
```
function BACKTRACK(assignment, csp):
    if assignment complete: return assignment
    var = SELECT-UNASSIGNED-VAR(assignment, csp)
    for value in DOMAIN-VALUES(var, assignment, csp):
        if value consistent with assignment:
            add {var = value} to assignment
            inferences = INFERENCE(assignment, csp)
            if inferences ≠ failure: add inferences to assignment
            result = BACKTRACK(assignment, csp)
            if result ≠ failure: return result
        remove {var = value} and inferences from assignment
    return failure
```

Domain-Values

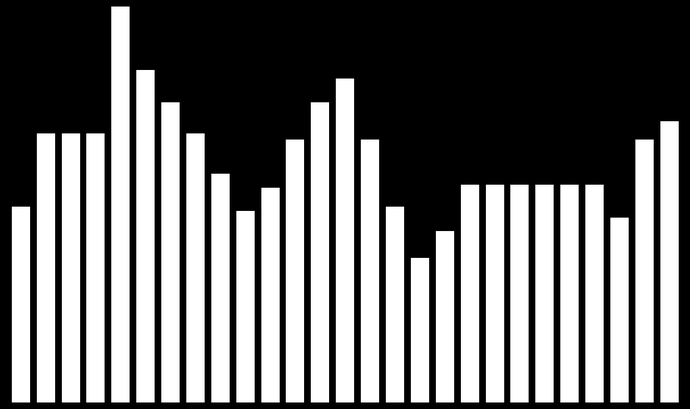
- **least-constraining values** heuristic: return variables in order by number of choices that are ruled out for neighboring variables
  - try least-constraining values first


Mon
A
{Mon, Tue, Wed}
B
C
{Tue, Wed}
{Mon, Tue, Wed}
D
F
{Mon, Tue}
E
{Mon, Tue, Wed}
G
Wed


Mon
A
{Mon, Tue, Wed}
B
C
Wed
{Mon, Tue, Wed}
D
F
{Mon, Tue}
E
{Mon, Tue, Wed}
G
Wed


Mon
A
Tue
B
C
Wed
Wed
D
F
Tue
Mon
E
G
Wed

Problem Formulation



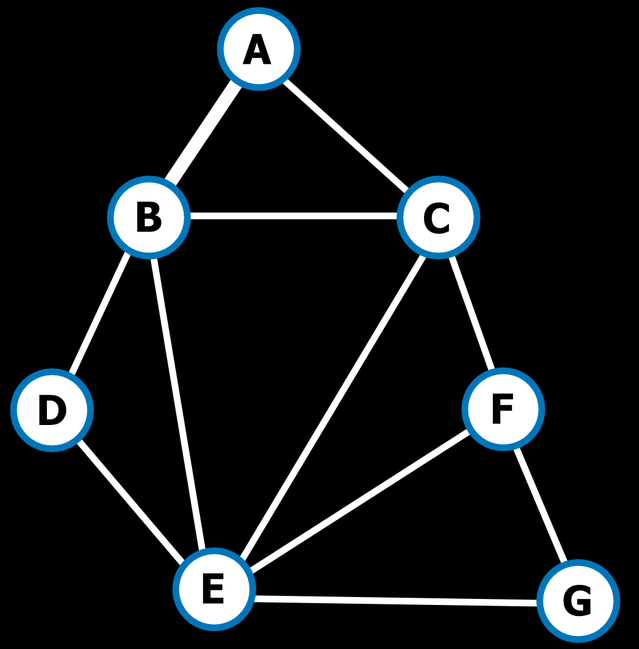
Local Search

$$50x_1 + 80x_2$$

$$5x_1 + 2x_2 \leq 20$$

$$(-10x_1) + (-12x_2) \leq -90$$

Linear Programming



Constraint Satisfaction

Optimization

python + AI

Introduction to Artificial Intelligence with Python