Data Structures Using C++ 2E

Chapter 6
Recursion

Objectives

- Learn about recursive definitions
- Explore the base case and the general case of a recursive definition
- Learn about recursive algorithm
- Learn about recursive functions
- Explore how to use recursive functions to implement recursive algorithms

Recursive Definitions

- Recursion
  - Process of solving a problem by reducing it to smaller versions of itself
- Example: factorial problem

  5! = 5 x 4 x 3 x 2 x 1 = 120

  - If *n* is a nonnegative, factorial of n (i.e., n!) defined as

Base case: solution obtained directly

$$0! = 1 \qquad \text{Eq 6-1}$$

$$n! = n \times (n - 1)! \quad \text{if } n > 0 \qquad \text{Eq 6-2}$$

General case: solution obtained indirectly using recursion

Smaller version of itself

Recursive Definitions (cont'd.)

- Recursion insight gained from factorial problem
  - Every recursive definition must have one (or more) base cases
  - General case must eventually reduce to a base case
  - Base case stops recursion
- Recursive algorithm
  - Finds problem solution by reducing problem to smaller versions of itself
- Recursive function
  - Function that calls itself

Recursive Definitions (cont'd.)

- Recursive function implementing the factorial function

```
int fact(int num)
{
    if (num == 0)
        return 1;
    else
        return num * fact(num - 1);
}
```

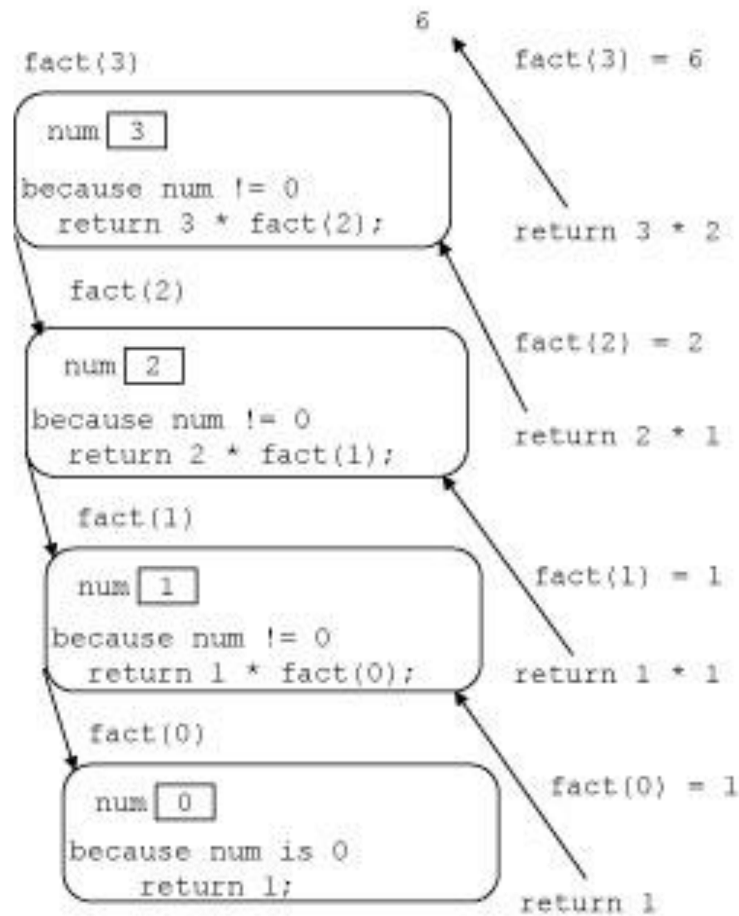


FIGURE 6-1 Execution of fact(4)

Recursive Definitions (cont'd.)

- Recursive function notable comments
  - Recursive function has unlimited number of copies of itself (logically)
  - Every call to a recursive function has its own
    - Code, set of parameters, local variables
  - After completing a particular recursive call
    - Control goes back to calling environment (previous call)
    - Current (recursive) call must execute completely before control goes back to the previous call
    - Execution in previous call begins from point immediately following the recursive call

Recursive Definitions (cont’d.)

- Direct and indirect recursion
  - Directly recursive function
    - Calls itself
  - Indirectly recursive function
    - Calls another function, eventually results in original function call
    - Requires same analysis as direct recursion
    - Base cases must be identified, appropriate solutions to them provided
    - Tracing can be tedious
  - Tail recursive function
    - Last statement executed: the recursive call, e.g., factorial

Recursive Definitions (cont'd.)

- Infinite recursion
  - Occurs if every recursive call results in another recursive call
  - Executes forever (in theory)
  - Call requirements for recursive functions
    - System memory for local variables and formal parameters
    - Saving information for transfer back to right caller
  - Finite system memory leads to
    - Execution until system runs out of memory
    - Abnormal termination of infinite recursive function

Recursive Definitions (cont'd.)

- Requirements to design a recursive function
  - Understand problem requirements
  - Determine limiting conditions
  - Identify base cases, providing direct solution to *each* base case
  - Identify general cases, providing solution to *each* general case in terms of smaller versions of itself
- No global/static variables! Pass program state as parameters of recursive function

In Class Exercises

```
int func(int x)
{
if (x == 0)
    return 2;
else if (x == 1)
    return 3;
else
    return (func(x - 1) + func(x - 2));
}
```

- func(5) = ?

```
void f(char ch)
{
   if (('A' <= ch) && (ch <= 'H')) {
      f(ch-1);
      cout << ch;
   } else
      cout << endl;
}
```

a. f('C')
b. f('G')
c. f('3')
d. f('C') if ch-1 is replaced by ch+1 in the function
e. f('C') if the output statement and the recursive function call to f() are interchanged

Largest Element in an Array

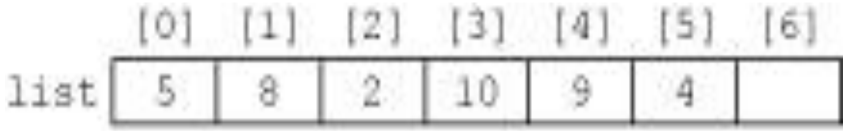


FIGURE 6-2 `list` with six elements

- `list`: array name containing elements
- `list[a]...list[b]` stands for the array elements `list[a], list[a + 1], ..., list[b]`
- Find largest element in `list[a]...list[b]`
  - `list` length =1
    - One element (largest)
  - `list` length >1

```
maximum(list[a],largest(list[a + 1]...list[b]))
```

Largest Element in an Array (cont'd.)

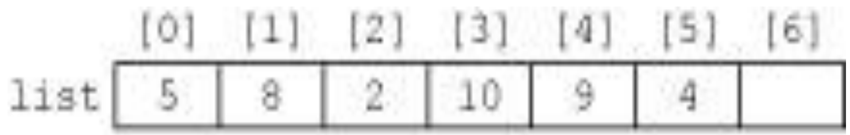


FIGURE 6-2 `list` with six elements

- `maximum(list[0],`
  `largest(list[1]...list[5]))`
- `maximum(list[1],`
  `largest(list[2]...list[5])`, etc.
- Every time previous formula used to find largest element in a sublist
  - Length of sublist in next call reduced by one
  - Eventually the sublist is of length 1

Largest Element in an Array (cont'd.)

- Recursive algorithm in pseudocode

Base Case: The size of the list is 1

The only element in the list is the largest element

General Case: The size of the list is greater than 1

To find the largest element in list[a]...list[b]

```
1. Find the largest element in list[a + 1]...list[b]
   and call it max
2. Compare the elements list[a] and max
   if (list[a] >= max)
       the largest element in list[a]...list[b] is list[a]
   otherwise
       the largest element in list[a]...list[b] is max
```

Largest Element in an Array (cont'd.)

- Recursive algorithm as a C++ function

```
int largest(const int list[], int lowerIndex, int upperIndex)
{
    int max;

    if (lowerIndex == upperIndex) //size of the sublist is one
        return list[lowerIndex];
    else
    {
        max = largest(list, lowerIndex + 1, upperIndex);

        if (list[lowerIndex] >= max)
            return list[lowerIndex];
        else
            return max;
    }
}
```

Largest Element in an Array (cont'd.)

	[0]	[1]	[2]	[3]
list	5	10	12	8

FIGURE 6-3 `list` with four elements

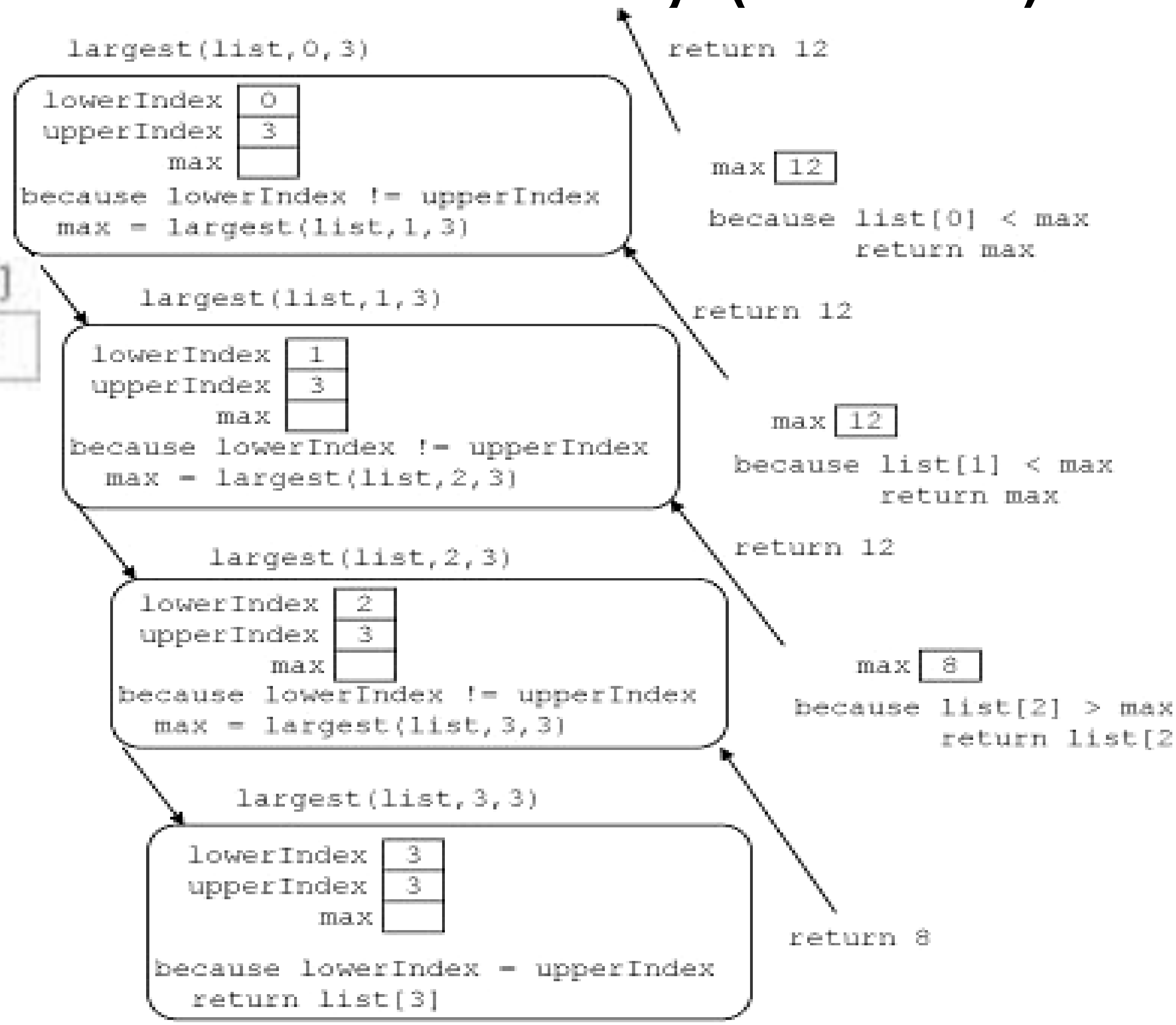
- Trace execution of the following statement

```
cout << largest(list, 0, 3) << endl;
```

- Review C++ program on page 362
  - Determines largest element in a list

Largest Element in an Array (cont'd.)

	[0]	[1]	[2]	[3]
list	5	10	12	8



No global/static variables! Pass program state as parameters of recursive function

FIGURE 6-4 Execution of `largest(list, 0, 3)`

Print a Linked List in Reverse Order

- Function `reversePrint`
  - Given list pointer, prints list elements in reverse order
- Figure 6-5 example
  - Links in one direction
  - Cannot traverse backward starting from last node

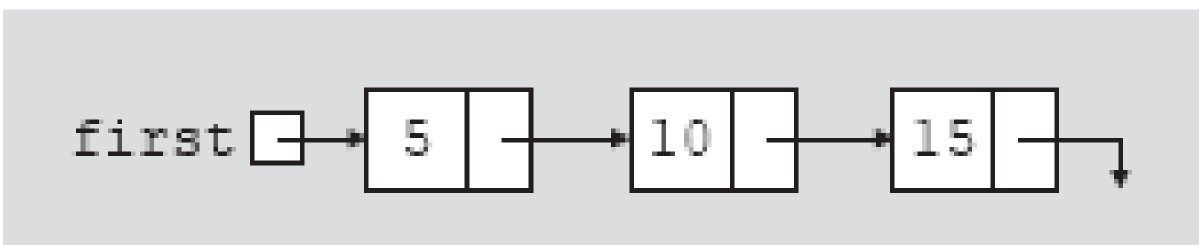


FIGURE 6-5 Linked list

Print a Linked List in Reverse Order (cont'd.)

- Cannot print first node info until remainder of list printed
- Cannot print second node info until tail of second node printed, etc.
- Every time tail of a node considered
  - List size reduced by one
  - Eventually list size reduced to zero
  - Recursion stops

Print a Linked List in Reverse Order (cont'd.)

- Recursive algorithm in pseudocode

Base Case: List is empty: no action

General Case: List is nonempty

1. Print the tail
2. Print the element

- Recursive algorithm in C++

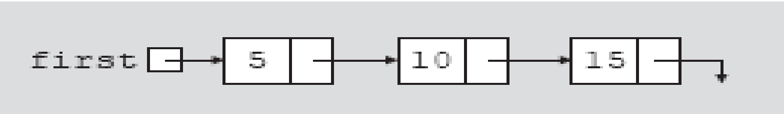
```
if (current != NULL)
{
   reversePrint(current->link);      //print the tail
   cout << current->info << endl;    //print the node
}
```

Print a Linked List in Reverse Order (cont'd.)

- Function template to implement previous algorithm and then apply it to a list

```
template <class Type>
void linkedListType<Type>::reversePrint
                          (nodeType<Type> *current) const
{
    if (current != NULL)
    {
        reversePrint(current->link);    //print the tail
        cout << current->info << " ";   //print the node
    }
}
```

Print a Linked List in Reverse Order (cont'd.)



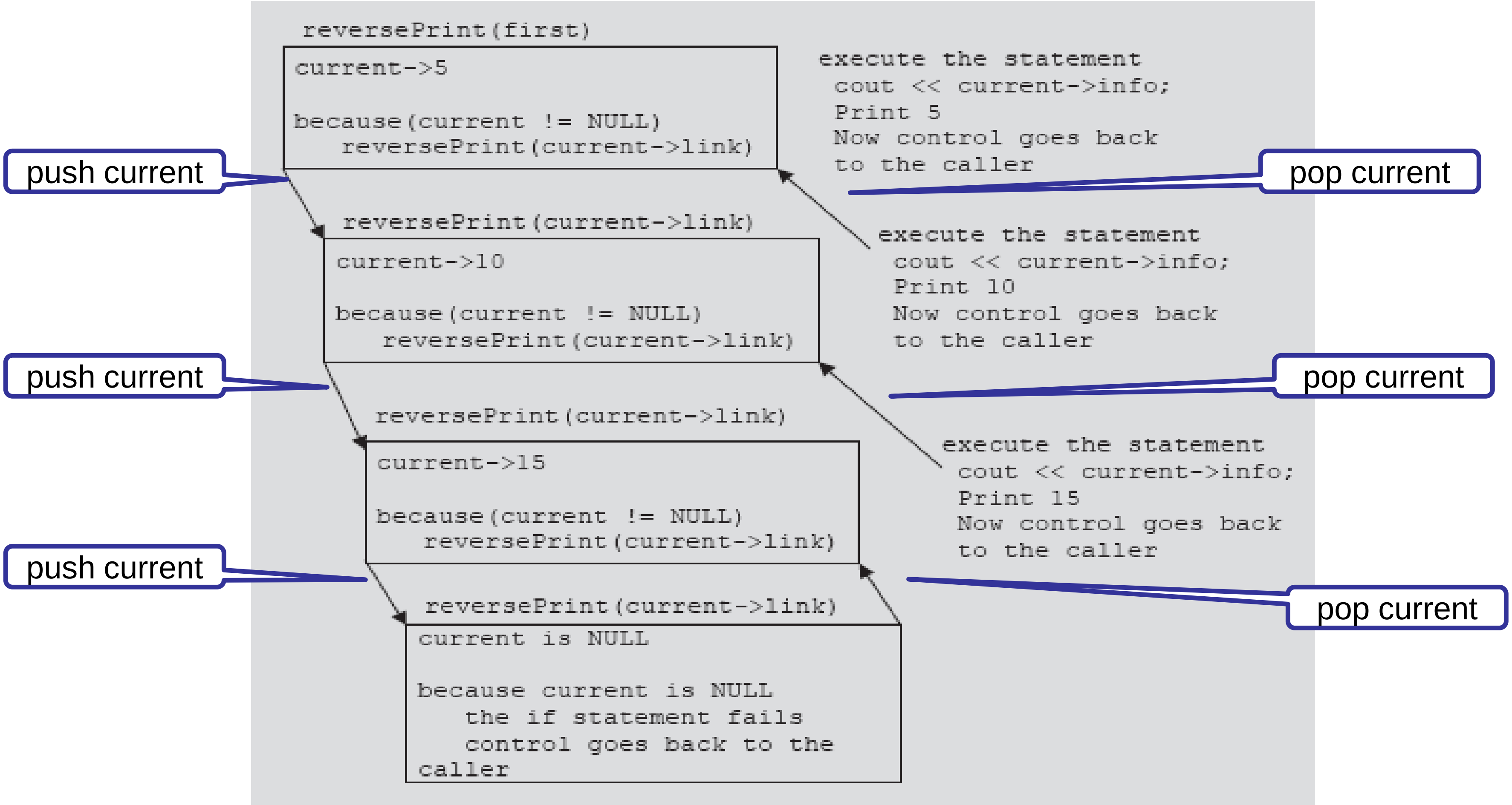


FIGURE 6-6 Execution of the statement `reversePrint(first);`

Print a Linked List in Reverse Order (cont'd.)

- The function `printListReverse`
  - Prints an ordered linked list contained in an object of the type `linkedListType`

```
template <class Type>
void linkedListType<Type>::printListReverse() const
{
    reversePrint(first);
    cout << endl;
}
```

Tips for Recursive Function

- Pass necessary state as formal parameters of recursive function
  - Each invocation of recursive function can access to the state info before/after making another recursive call
  - Do NOT utilize global variable
  - Do NOT utilize static variable

Fibonacci Number

- Sequence: 1, 1, 2, 3, 5, 8, 13, 21, 34, . . .
- Sequence: 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, . . .
- Given first two numbers (a_1 and a_2)
  – *n*th number a_n, $n >= 3$, of sequence given by:
  $a_n = a_{n-1} + a_{n-2}$
- Recursive function: `rFibNum`
  – Determines desired Fibonacci number
  – Parameters: three numbers representing
    - first two numbers of the Fibonacci sequence, and
    - a number *n*, the desired *n*th Fibonacci number
  – Returns the *n*th Fibonacci number in the sequence

Fibonacci Number (cont'd.)

- Third Fibonacci number
  - Sum of first two Fibonacci numbers
- Fourth Fibonacci number in a sequence
  - Sum of second and third Fibonacci numbers
- Calculating fourth Fibonacci number
  - Add second Fibonacci number and third Fibonacci number

Fibonacci Number (cont'd.)

- Recursive algorithm
  - Calculates *n*th Fibonacci number
    - *a* denotes first Fibonacci number
    - *b* denotes second Fibonacci number
    - *n* denotes *n*th Fibonacci number

$$rFibNum(a,b,n) = \begin{cases} a & \text{if } n = 1 \\ b & \text{if } n = 2 \\ rFibNum(a,b,n-1) + & \\ rFibNum(a,b,n-2) & \text{if } n > 2. \end{cases} \quad \text{(Equation 6-3)}$$

Fibonacci Number (cont'd.)

- Recursive function implementing algorithm
- Trace code execution
- Review code on page 368 illustrating the function `rFibNum`

```
int rFibNum(int a, int b, int n)
{
    if (n == 1)
        return a;
    else if (n == 2)
        return b;
    else
        return rFibNum(a, b, n - 1) + rFibNum(a, b, n - 2);
}
```

Fibonacci Number (cont'd.)

No global/static variables! Pass program state as parameters of recursive function

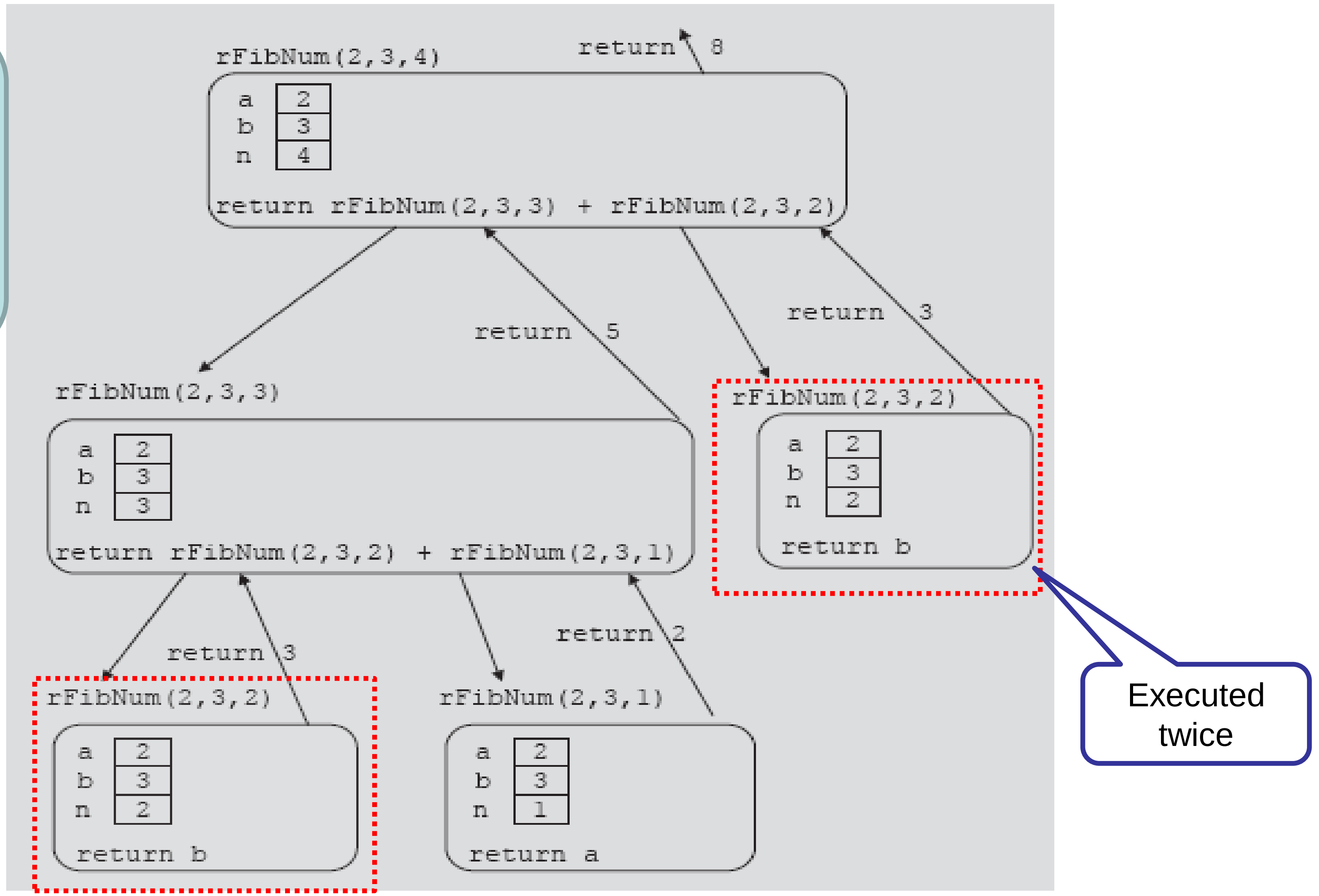


FIGURE 6-7 Execution of `rFibNum(2, 3, 4)`

Tower of Hanoi

- Env: 3 needles and 64 disks
- Objective
  - Move 64 disks from first needle to third needle
- Rules
  - Only one disk can be moved at a time
  - Removed disk must be placed on one of the needles
  - A larger disk cannot be placed on top of a smaller disk

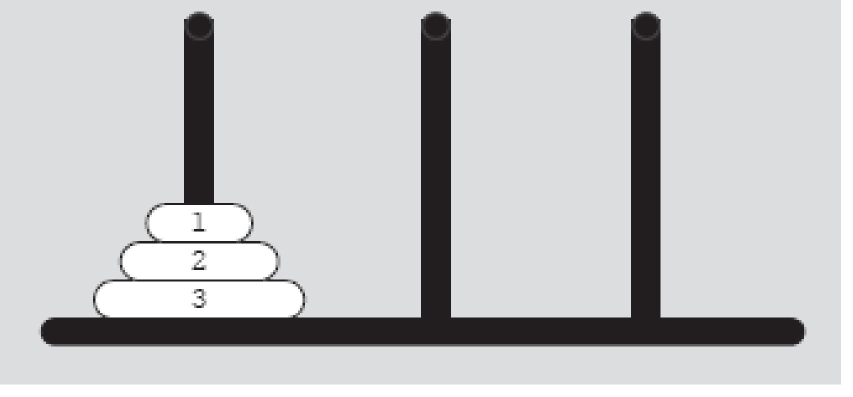


FIGURE 6-8 Tower of Hanoi problem with three disks

Tower of Hanoi (cont'd.)

- Case: first needle contains only one disk
  - Move disk directly from needle 1 to needle 3
- Case: first needle contains only two disks
  - Move first disk from needle 1 to needle 2
  - Move second disk from needle 1 to needle 3
  - Move first disk from needle 2 to needle 3
- Case: first needle contains three disks
  - Move first two disks from needle 1 to needle 2
  - Move disk 3 directly from needle 1 to needle 3
  - Move disks 1 & 2 from needle 2 to needle 3

Tower of Hanoi (cont'd.)

- http://www.cosc.canterbury.ac.nz/mukundan/dsal/ToHdb.html
- http://math.rice.edu/~lanius/domath/hanoi.html

Tower of Hanoi (cont'd.)

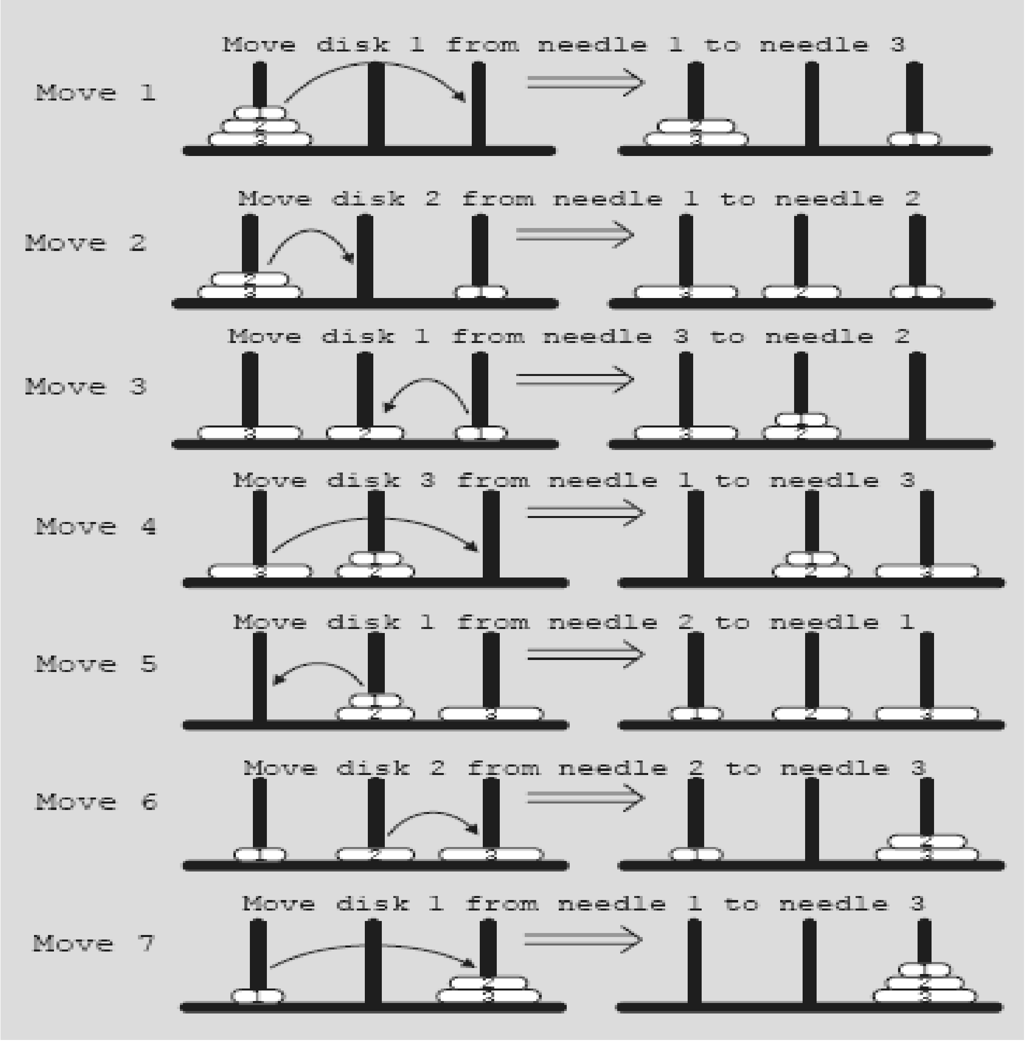


FIGURE 6-9 Solution to Tower of Hanoi problem with three disks

Tower of Hanoi (cont'd.)

- Generalize problem to the case of 64 disks
  - Recursive algorithm in pseudocode

Suppose that needle 1 contains n disks, where $n \geq 1$.

1. Move the top $n - 1$ disks from needle 1 to needle 2, using needle 3 as the intermediate needle.
2. Move disk number n from needle 1 to needle 3.
3. Move the top $n - 1$ disks from needle 2 to needle 3, using needle 1 as the intermediate needle.

Tower of Hanoi (cont'd.)

- Generalize problem to the case of 64 disks
  - Recursive algorithm in C++

```
void moveDisks(int count, int needle1, int needle3, int needle2)
{
    if (count > 0)
    {
        moveDisks(count - 1, needle1, needle2, needle3);

        cout << "Move disk " << count << " from " << needle1
             << " to " << needle3 << "." << endl;

        moveDisks(count - 1, needle2, needle3, needle1);
    }
}
```

Tower of Hanoi (cont'd.)

- Analysis of Tower of Hanoi
  - A minimum number of moves of $2^n - 1$ is needed for n disks
    - If n = 3, total 7 moves
  - Time necessary to move all 64 disks from needle 1 to needle 3
    - $2^{64} \sim 1.6 \times 10^{19}$
    - Manually (1 move/second): roughly 5×10^{11} years ~ 500 billion years
      - Universe is about 15 billion years old (1.5×10^{10})
    - Computer (10^9 moves/second): 500 years

Converting a Number from Decimal to Binary

- Convert nonnegative integer in decimal format (base 10) into equivalent binary number (base 2)
- Rightmost bit of *x*
  - Remainder of *x* after division by two
- Recursive algorithm pseudocode
  - Binary(num) denotes binary representation of num

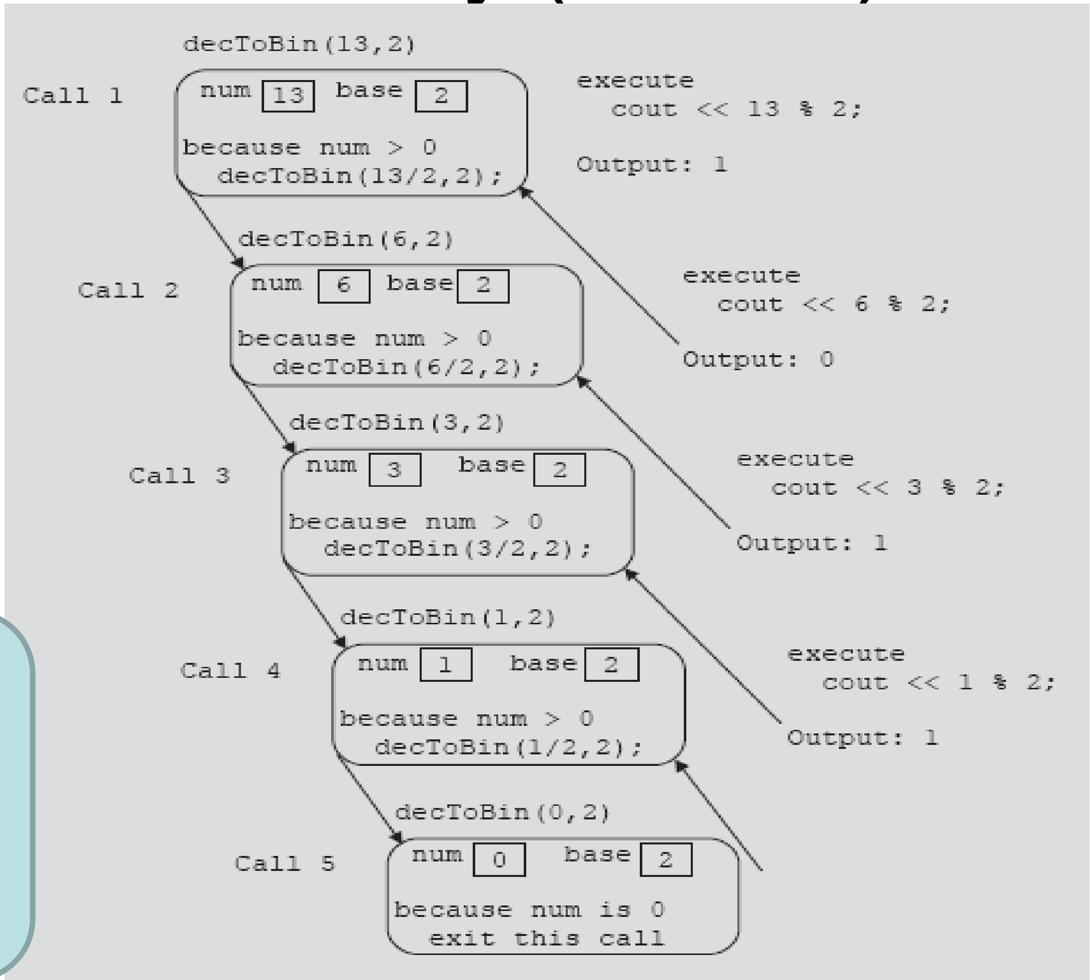
1. binary(num) = num if num = 0.
2. binary(num) = binary(num / 2) followed by num % 2 if num > 0.

Converting a Number from Decimal to Binary (cont'd.)

- Recursive function implementing algorithm

```
void decToBin(int num, int base)
{
    if (num > 0)
    {
        decToBin(num / base, base);
        cout << num % base;
    }
}
```

Converting a Number from Decimal to Binary (cont'd.)



No global/static variables! Pass program state as parameters of recursive function

FIGURE 6-10 Execution of `decToBin(13, 2)`

Recursion or Iteration?

- Dependent upon nature of the solution and efficiency
- Efficiency
  - Overhead of recursive function: execution time and memory usage
    - Given speed memory of today's computers, we can depend more on how programmer envisions solution
  - Use of programmer's time
  - Any program that can be written recursively can also be written iteratively

Recursion and Backtracking: 8-Queens Puzzle

- 8-queens puzzle
  - Place 8 queens on a chess-board
    - No two queens can attack each other
  - Nonattacking queens
    - Cannot be in same row, same column, same diagonals

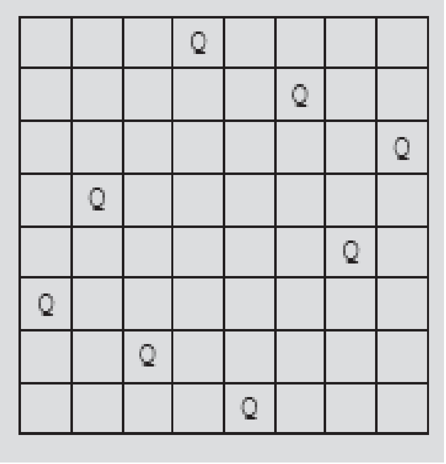


FIGURE 6-11 A solution to the 8-queens puzzle

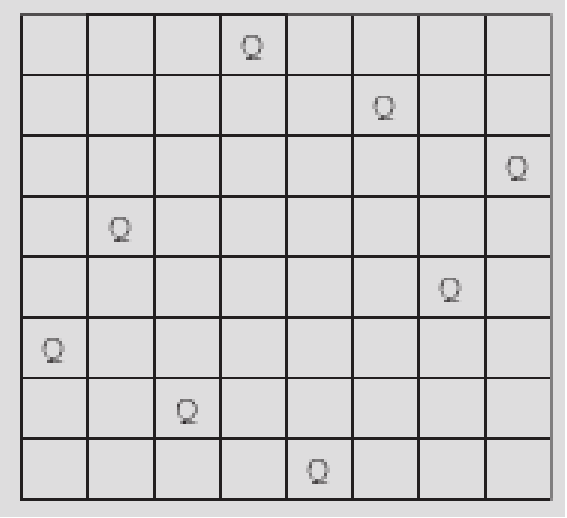
Recursion and Backtracking: 8-Queens Puzzle (cont'd.)

- Backtracking algorithm
  - Find problem solutions by constructing partial solutions
  - Ensures partial solution does not violate requirements
  - Extends partial solution toward completion
  - If partial solution does not lead to a solution (dead end)
    - Algorithm backs up
    - Removes most recently added part
    - Tries other possibilities

Recursion and Backtracking: 8-Queens Puzzle (cont'd.)

- *n*-Queens Puzzle
  - In backtracking, solution represented as
    - *n*-tuple $(x_1, x_2, . . ., x_n)$
    - Where x_i is an integer such that

      $1 <= x_i <= n$
    - x_i specifies column number, where to place the *i*th queen in the *i*th row
  - Solution example for Figure 6-11
    - (4,6,8,2,7,1,3,5)
    - Number of 8-tuple representing a solution: 8!



Recursion and Backtracking: 8-Queens Puzzle (cont’d.)

- *n*-Queens Puzzle (cont’d.)
  - 4-queens puzzle

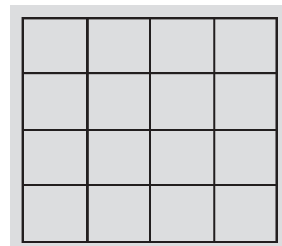


FIGURE 6-12 Square board for the 4-queens puzzle

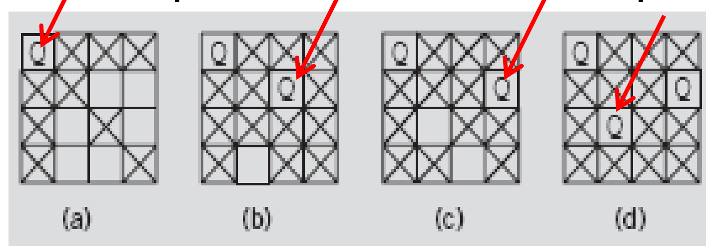


FIGURE 6-13 Finding a solution to the 4-queens puzzle

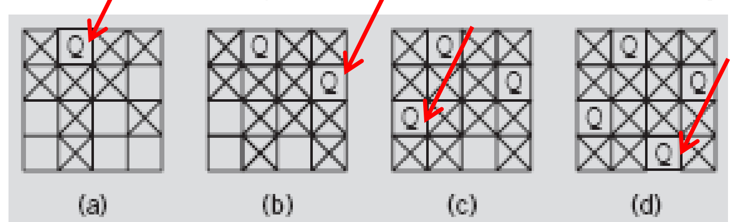


FIGURE 6-14 A solution to the 4-queens puzzle (1,3,0,2)

Recursion and Backtracking: 8-Queens Puzzle (cont'd.)

- Backtracking and the 4-Queens Puzzle
  - Rows and columns numbered zero to three
  - Backtracking algorithm can be represented by a tree

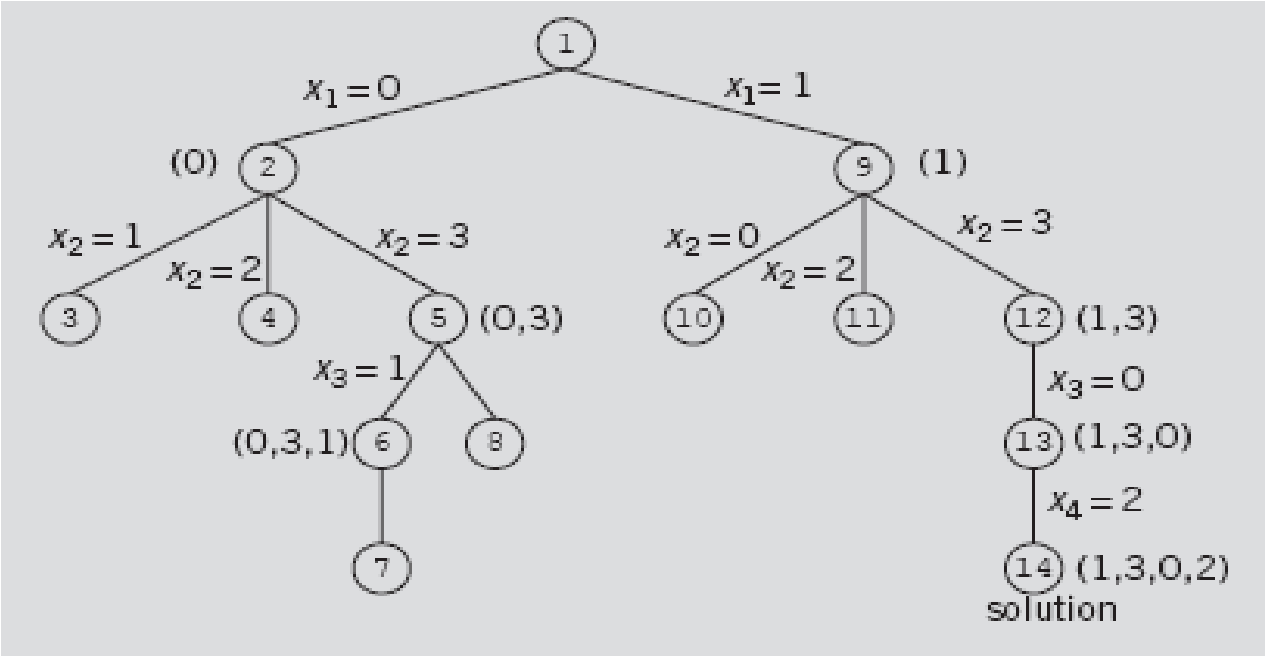


FIGURE 6-15 4-queens tree

Recursion and Backtracking: 8-Queens Puzzle (cont'd.)

- 8-Queens Puzzle
  - Easy to determine whether two queens in same row or column
  - Determine if two queens on same diagonal
    - Given queen at position (i, j), (row i and column j), and another queen at position (k, l), (row k and column l)
    - Two queens on the same diagonal if $|j – l| = |i – k|$, where

      $|j – l|$ is the absolute value of $j – l$ and so on
  - Solution represented as an 8-tuple
    - Use the array `queensInRow` of size eight
    - Where `queensInRow[k]` specifies column position of the *k*th queen in row *k*

Recursion and Backtracking: 8-Queens Puzzle (cont'd.)

- 8-Queens Puzzle (cont'd.)

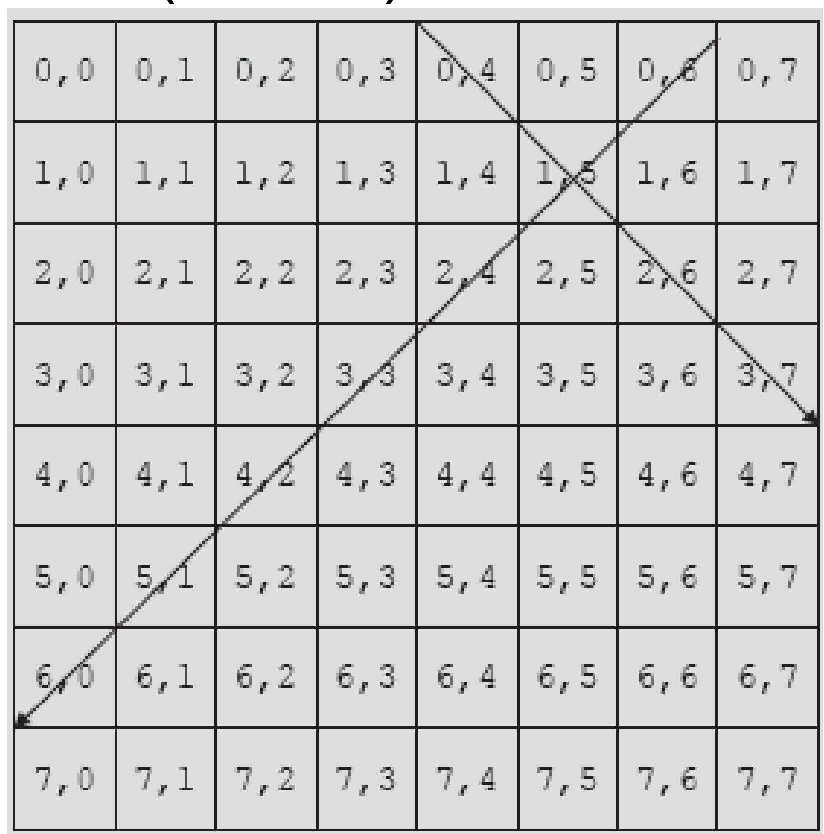


FIGURE 6-16 8 x 8 square board

Recursion and Backtracking: 8-Queens Puzzle (cont'd.)

- 8-Queens Puzzle (cont'd.)
  - General algorithm for the function `canPlaceQueen(k, i)`

```
bool nQueensPuzzle::canPlaceQueen(int k, int i)
{
    for (int j = 0; j < k; j++)
        if ((queensInRow[j] == i)
             || (abs(queensInRow[j] - i) == abs(j-k)))
            return false;
    return true;
}
```

Recursion and Backtracking: 8-Queens Puzzle (cont'd.)

- 8-Queens Puzzle (cont'd.)
  - Implement the backtracking and find all solutions

```
void nQueensPuzzle::queensConfiguration(int k)
{
    for (int i = 0; i < noOfQueens; i++)
    {
        if (canPlaceQueen(k, i))
        {
            queensInRow[k] = i;  //place the kth queen in column i
            if (k == noOfQueens - 1)  //all the queens are placed
                printConfiguration(); //print the n-tuple
            else
                queensConfiguration(k + 1); //determine the place
                                            //for the (k+1)th queen
        }
    }
}
```

Recursion, Backtracking, and Sudoku

- Recursive algorithm
  - Start at first row and find empty slot
  - Find first number to place in this slot
  - Find next empty slot, try to place a number in that slot
  - Backtrack if necessary; place different number
  - No solution if no number can be placed in slot

Fill the 9x9 grid with numbers 1 to 9 such that each number appears exactly once in each row, each column, and each 3x3 smaller grid

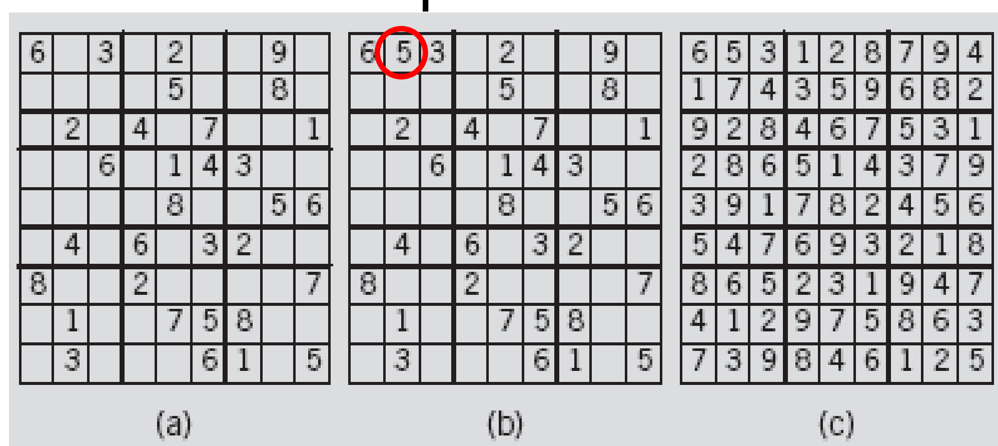


FIGURE 6-17 Sudoku problem and its solution

Recursion, Backtracking, and Sudoku (cont'd.)

- See code on page 384
  - Class implementing Sudoku problem as an ADT
  - General algorithm in pseudocode
    - Find the position of the first empty slot in the partially filled grid
    - If the grid has no empty slots, return true and print the solution
    - Suppose the variables row and col specify the position of the empty grid position

Recursion, Backtracking, and Sudoku (cont'd.)

- General algorithm in pseudocode (cont'd.)

```
for (int digit = 1; digit <= 9; digit++)
{
   if (grid[row][col] <> digit)
   {
       grid[row][col] = digit;
       recursively fill the updated grid;
       if the grid is filled successfully, return true,
       otherwise remove the assigned digit from grid[row][col]
       and try another digit.
    }
  If all the digits have been tried and nothing worked, return false.
```

Recursion, Backtracking, and Sudoku (cont'd.)

- Function definition

```
bool sudoku::solveSudoku()
{
    int row, col;

    if (findEmptyGridSlot(row, col))
    {
        for (int num = 1; num <= 9; num++)
        {
            if (canPlaceNum(row, col, num))
            {
                grid[row][col] = num;
                if (solveSudoku()) //recursive call
                    return true;
                grid[row][col] = 0;
            }
        }

        return false; //backtrack
    }
    else
        return true; //there are no empty slots
}
```

```
class sudoku
{
public:
    sudoku();
      //default constructor
      //Postcondition: grid is initialized to 0

    sudoku(int g[][9]);
      //constructor
      //Postcondition: grid = g

    void initializeSudokuGrid();
      //Function to prompt the user to specify the numbers of the
      //partially filled grid.
      //Postcondition: grid is initialized to the numbers
      //    specified by the user.

    void initializeSudokuGrid(int g[][9]);
      //Function to initialize grid to g
      //Postcondition: grid = g;

    void printSudokuGrid();
      //Function to print the sudoku grid.

    bool solveSudoku();
      //Funtion to solve the sudoku problem.
      //Postcondition: If a solution exits, it returns true,
      //    otherwise it returns false.
```

```
    bool findEmptyGridSlot(int &row, int &col);
      //Function to determine if the grid slot specified by
      //row and col is empty.
      //Postcondition: Returns true if grid[row][col] = 0;

    bool canPlaceNum(int row, int col, int num);
      //Function to determine if num can be placed in
      //grid[row][col]
      //Postcondition: Returns true if num can be placed in
      //    grid[row][col], otherwise it returns false.

    bool numAlreadyInRow(int row, int num);
      //Function to determine if num is in grid[row][]
      //Postcondition: Returns true if num is in grid[row][],
      //    otherwise it returns false.

    bool numAlreadyInCol(int col, int num);
      //Function to determine if num is in grid[row][]
      //Postcondition: Returns true if num is in grid[row][],
      //    otherwise it returns false.

    bool numAlreadyInBox(int smallGridRow, int smallGridCol,
                         int num);
      //Function to determine if num is in the small grid
      //Postcondition: Returns true if num is in small grid,
      //    otherwise it returns false.

private:
    int grid[9][9];
};
```

Recursion, Backtracking, and Sudoku (cont'd.)

- Function definition

```
bool sudoku::findEmptyGridSlot(int &row, int &col)
{
    for (row = 0; row < 9; row++)
        for (col = 0; col < 9; col++)
            if (grid[row][col] == 0)
                return true;
    return false;
}

bool sudoku::canPlaceNum(int row, int col, int num)
{
    return (!numAlreadyInRow(row, num)
          && !numAlreadyInCol(col, num)
          && !numAlreadyInBox(row - row % 3 , col - col % 3, num));
}
```

Discussion

- Describe situations in which it is appropriate to use iteration over recursion.
- Discuss possible recursive implementations of programs previously implemented iteratively

Summary

- Recursion
  - Solve problem by reducing it to smaller versions of itself
  - Base(s): obtain the result directly
  - General case(s): smaller version of itself, indirect result
- Recursive algorithms implemented using recursive functions
  - Direct, indirect, and infinite recursion
  - No global/static variables!
- Many problems solved using recursive algorithms
- Choosing between recursion and iteration
  - Nature of solution; efficiency requirements
- Backtracking
  - Problem solving; iterative design technique

Resources

- http://cis.stvincent.edu/html/tutorials/swd/recur/recur.html
- http://www.ibm.com/developerworks/linux/library/l-recurs/index.html
- http://xlinux.nist.gov/dads/HTML/recursion.html
- http://xlinux.nist.gov/dads//HTML/towersOfHanoi.html
- http://www.cosc.canterbury.ac.nz/mukundan/dsal/ToHdb.html
- http://math.rice.edu/~lanius/domath/hanoi.html
- http://www.drdobbs.com/tools/parallelizing-n-queens-with-the-intel-pa/214303519

Self Exercises

- Programming Exercises: 3, 5, 6, 7, 9, 10, 15