1.

We are using the “bottom up solution”, where we calculate smaller subproblems first and build them up to reach our final solution. This allows us to cache subproblem results in a table from left to right and check before we call a certain element if we can use an existing ansser, so that we only have to perform calculations for a given element once. This way we are finding the main solution in a efficient way due to fact that this problem has overlapping subproblems and we are only calculating each subproblem once and resusing those answers in our build up phase. This is the steps changedp we will take to fill in the table:

First create a vector to store minimum number of coins needed to sum to each change value i

Initialize vector values to infinity to signify no coins

Initialize first vector element to 0, this is the base case. This corresponds to cell 0,0 in our table

Build solution one by one by first iterating through the values of the change up to the desired change value. In our table, x axis values will correspond to each integer from 0 to change value.

For each value up to change value, iterate through coin set. In our table, y axis values will correspond to each integer in coin set. Note at the top row values will be same as x values.

As long as change value is greater or equal to current coin set element value j. In our table, if the change value is less than the coin set value then it does not get a mini-solution calculated and is ignored.

Take the minimum of mini-solution for j and mini-solution for j - current coin set element value + 1, where mini-solution is the minimum number of required to make change for respective change value. In our table, considering that the change value is greater than coin set value we will either add that coin set value

or replace existing coins in solution while adding that coin (the subtracting coin set value number of elements while adding 1 coin with coin set value demoniation) – depending on which returns the minimum value.

|  |
| --- |
| At the end of double for loop processing, main solution will be minimum mini-solution and so return the minimum number of coins needed to sum to each change value i. In our table we will take the bottom right most cell to be our final solution for minimum change required to make some change value. |

2.

# Brute Force or Divide and Conquer Algorithm

To make change for A cents using divide and conquer, first we find the minimum number of coins needed to make change for every value x < A. The solution for finding minimum number of coins to make change for A is found by taking the minimum of these mini-solutions. Translated into a formula C[A] = 1 + C[A-x] where 1 is the solution in terms of A and C[A-x] is the mini-solutions.

## Psuedocode for Brute Force or Divide and Conquer Algorithm

Main function for returning main solution for minimum number of coins to make V change

Create and initialize coin set objects representing current and minimum coin sets for use in helper function

Initialize solution for minimum number of coins to make V change to infinity

Call recursive helper function to run brute force algorithm

Once the recursive helper function has returned the minimum solution, record the actual coins in the minimum solution coin set

Return the minimum number of coins to make V change

Recursive helper function for finding mini-solutions for minimum numer of coins to make i change where i < V

Base case: If V is 0, then 0 coins are needed

Constant comparison: If V < i, then i cannot be used

Recursive case: If V >= i, then i can possibly be used

Recursively find minimum number of coins needed to make V – i change

Update the minimum solution with the minimum of current mini-solution and current minimum

Return the minimum solution

## Source Code for Brute Force or Divide and Conquer Algorithm

/\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

\* \* Function name: change slow

\* \* Parameters: Vector of coin set, int representing V, Vector of actual coins in set

\* \* Brute force method

\* \* Return value: minimum number coins to create V change

\* \* Description: This algorithm can be viewed as divide-and-conquer, or as brute force.

\* \* This solution is very recursive and runs in exponential time.

\* \* Credit: http://www.geeksforgeeks.org/find-minimum-number-of-coins-that-make-a-change/

\* \* http://romanenco.com/coin-change-problem/

\* \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*/

int changeslow(std::vector<int> &coinSet, int coinSetValue, std::vector<int> &actualCoinsUsed)

{

/\* CS struct consists of int representing coin set amount and int vector representing actual coins in a coin set \*/

CS minimumCoinSet;

/\* Create and initialize coin set objects representing current and minimum coin sets for use in helper function \*/

for ( unsigned int i = 0; i < coinSet.size(); i++ )

{

minimumCoinSet.actualCoins.push\_back(0);

}

/\* Initialize solution for minimum number of coins to make V change to infinity \*/

minimumCoinSet.numberCoins = INT\_MAX; //algorithm library has constant for max

CS currentCoinSet;

for ( unsigned int i = 0; i < coinSet.size(); i++ )

{

currentCoinSet.actualCoins.push\_back(0);

}

/\* Since this coin set will be the current one being tested against the min, initalize it to 0 amount coins \*/

currentCoinSet.numberCoins = 0;

/\* Call recursive helper function to run brute force algorithm \*/

recursiveBrute( coinSetValue, coinSet, minimumCoinSet, currentCoinSet );

/\* Once the recursive helper function has returned the minimum solution, record the actual coins in the minimum solution coin set \*/

for ( unsigned int i = 0; i < coinSet.size(); i++ )

{

actualCoinsUsed.push\_back( minimumCoinSet.actualCoins[i] );

}

/\* Return the minimum number of coins to make V change \*/

return minimumCoinSet.numberCoins;

}

/\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

\* \* Function name: recursive brute

\* \* Parameters: Vector of coin set, int representing V, coin set structs for current coin set and current min coin set

\* \* Return value: Does not return as minimum coin set vector is recorded in the function

\* \* Description: Recursive helper method that is called recursively based on psuedocode

\* \* Credit: http://www.geeksforgeeks.org/find-minimum-number-of-coins-that-make-a-change/

\* \* http://romanenco.com/coin-change-problem/

\* \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*/

void recursiveBrute(int coinSetValue, std::vector<int> coinSet, CS &minimumCoinSet,CS currentCoinSet )

{

/\* Base Case: We can make change using exactly one coin, then that is a minimum \*/

if ( coinSetValue == 0 )

{

/\* If there are less coins in current coin set than current min coin set \*/

if ( currentCoinSet.numberCoins < minimumCoinSet.numberCoins )

{

/\* Then update the new min coin set with amount value and actual coin list \*/

minimumCoinSet.numberCoins = currentCoinSet.numberCoins;

minimumCoinSet.actualCoins = currentCoinSet.actualCoins;

}

return;

}

/\* If there are more coins in current set than minimum set then its not new min so return \*/

if ( currentCoinSet.numberCoins > minimumCoinSet.numberCoins )

{

return;

}

/\* Try every coin that has smaller value than V

Find the minimum number of coins needed to make i cents \*/

for ( int j = coinSet.size() - 1; j >= 0; j-- )

{

/\* If we haven't reached the K yet then we should keep recursively calling on K - i \*/

if ( coinSetValue >= coinSet[j] )

{

/\* With each mini-solution create a new coin set object and update its amount and coins used \*/

CS newSet;

newSet.numberCoins = currentCoinSet.numberCoins + 1;

newSet.actualCoins = currentCoinSet.actualCoins;

newSet.actualCoins[j]++;

/\* Find the minimum number of coins needed to make K - i cents \*/

recursiveBrute( coinSetValue - coinSet[j], coinSet, minimumCoinSet, newSet);

}

}

}

# Dynamic Programming Algorithm

We are using the “bottom up solution”, where we calculate smaller subproblems first and build them up to reach our final solution. This allows us to cache subproblem results in a table and check before we call a certain element if we can use an existing ansser, so that we only have to perform calculations for a given element once. This way we are finding the main solution in a efficient way due to fact that this problem has overlapping subproblems and we are only calculating each subproblem once and resusing those answers in our build up phase.

## Psuedocode for Dynamic Programming Algorithm

First create a vector to store minimum number of coins needed to sum to each change value i

Initialize vector values to infinity to signify no coins

Inititialize first vector element to 0, this is the case case

Build solution one by one by first iterating through the values of the change up to the desired change value

For each value up to change value, iterate through coin set

As long as change value is greater or equal to current coin set element value j

Take the minimum of mini-solution for j and mini-solution for j - current coin set element value + 1, where mini-solution is the minimum number of required to make change for respective change value

|  |
| --- |
| At the end of double for loop processing, main solution will be minimum mini-solution and so return the minimum number of coins needed to sum to each change value i |
|  |

|  |
| --- |
|  |

**Source Code for Dynamic Programming Algorithm**

|  |
| --- |
| /\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*  \* Description: dpChange uses dynamic programming approach to find the minimum number of coins  \* that sum to the value of makeChangeVal from the set of coins coinSet.  \* Precondition:coinSet contains a set of integers, makeChangeVal is a number > 0  \* Postcondition: The number of coins and the solution set is stored in the coinChange struct  \* result.  \* \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*/  void Changedp::dpChange(std::vector<int> &coinSet, int makeChangeVal, struct coinChange &result){  std::vector<struct coinChange> values;  //load the values array with coinChange structs:  //values will store the min num of coins needed to sum to value i  //initialize values to infinity to signify no coins  for(int i = 0; i <= makeChangeVal; ++i){  struct coinChange value;  values.push\_back(value);  values.at(i).coins = std::numeric\_limits<int>::max();  //initialize each result vec to show zero coins  for(int x = 0; x < coinSet.size(); ++x){  values.at(i).resultVec.push\_back(0);  }  }  //intialize 0 value to 0  values.at(0).coins = 0;  //outer loop iterates through the values of the change up to the makeChangeVal  for(int change = 0; change < values.size(); ++change){  //inner loop iterates through the coin set and finds the fewest num of coins to make change  //for the change value.  for(int x = 0; x < coinSet.size(); ++x){  //store fewest num of coins required to make change in values array  if(change >= coinSet.at(x)){  if(values.at(change - coinSet.at(x)).coins + 1 <= values.at(change).coins){  //found a better solution for this problem so save it in values array  for(int i = 0; i < coinSet.size(); ++i){ values.at(change).resultVec.at(i) = values.at(change - coinSet.at(x)).resultVec.at(i); }  //now add the coin just found  ++values.at(change).resultVec.at(x);  }  values.at(change).coins = std::min(values.at(change).coins, values.at(change - coinSet.at(x)).coins + 1);  }  }  }  //finished so set the result and return  //Result is stored in last value of values vector coinChange struct  result.coins = values.at(makeChangeVal).coins;  for(int i = 0; i < coinSet.size(); ++i){  result.resultVec.push\_back(values.at(makeChangeVal).resultVec.at(i));  }  } |
|  |
|  |
|  |

# Greedy Algorithm

To make change for A cents using greedy algorithm, from greatest to least value for each element of the vector we find how many times its value can be used to make V change, finding the “optimal” solution in terms of that element. It continues this for each element while V is greater than the current change value. So the result may consist of “optimal” solutions in terms of individual elements but a “suboptimal” solution in terms of the entire set.

## Psuedocode for Greedy Algorithm

Create and initialize coin set object representing minimum coin count for each coin set element

while the current change value is greater than 0 we can keep going

for each element vector[i] from greatest to smallest (since input data ascending)

Initalize coin count for that element vector[i]

For each element vector[i], while current change value greater than or equal to vector[i]

Increment coin count for vector[i]

Subtract vector[i] from current change value

Update i element of coin set object with coin count vector[i]

Loop through coin set object to sum up values of coin counts for vector elements

Return sum

## Source Code for Greedy Algorithm

/\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

\* \* Function name: change greedy

\* \* Parameters: Vector of coin set, int representing V, Vector of coin counts

\* \* Return value: Returns sum of coin count values representing minimum coins to make V change

\* \* Description: Another approach to coin change problem is the greedy approach. This implementation is called changegreedy.

\* \* This is also “naive” since it may not be optimal.

\* \* Credits: http://everythingcomputerscience.com/algorithms/Greedy\_Algorithm.html

\* \* http://stackoverflow.com/questions/13557979/why-does-the-greedy-coin-change-algorithm-not-work-for-some-coin-sets

\* \* https://www.quora.com/What-is-an-intuitive-explanation-of-greedy-algorithms

\* \* https://www.youtube.com/watch?v=AUIgt5y5Eyo

\* \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*/

int changegreedy(std::vector<int> &coinSet, int coinSetValue, std::vector<int> &coinCount)

{

int sum = 0;

/\* Create and initialize coin set object representing minimum coin count for each coin set element \*/

for( unsigned int i = 0; i < coinSet.size(); i++ )

coinCount.push\_back(0);

/\* while change value is greater than 0 we can keep going \*/

while ( coinSetValue > 0 )

{

/\* for each next greatest element (starting from end since this data input is ascending)vector[i] initalize coin count for that element vector[i] \*/

for (long i = coinSet.size() - 1; i >= 0; i--)

{

int tempcoincount = 0;

/\* For each element vector[i], while current change value greater than or equal to vector[i]\*/

while ( coinSetValue >= coinSet[i] )

{

/\* Increment coin count for vector[i] and subtract vector[i] from current change value \*/

tempcoincount++;

coinSetValue -= coinSet[i];

}

/\* Update i element of coin set object with coin count vector[i] \*/

coinCount.at(i) = tempcoincount;

}

}

/\* Loop through coin set object to sum up values of coin counts for vector elements \*/

for ( unsigned int j = 0; j < coinCount.size(); j++ )

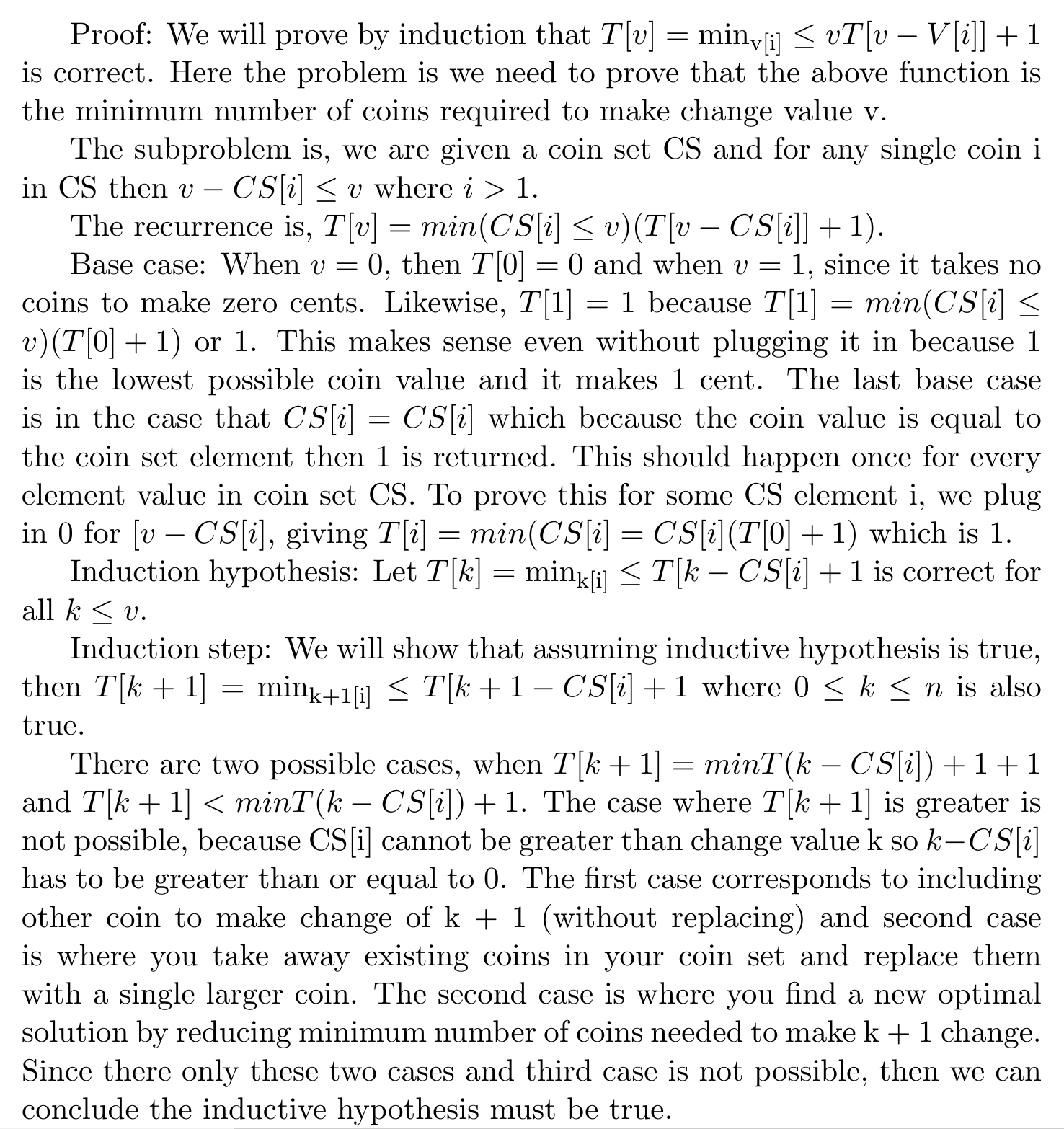
sum += coinCount[j];

/\* sum of coin count values is minimum coins to make V change \*/

return sum;

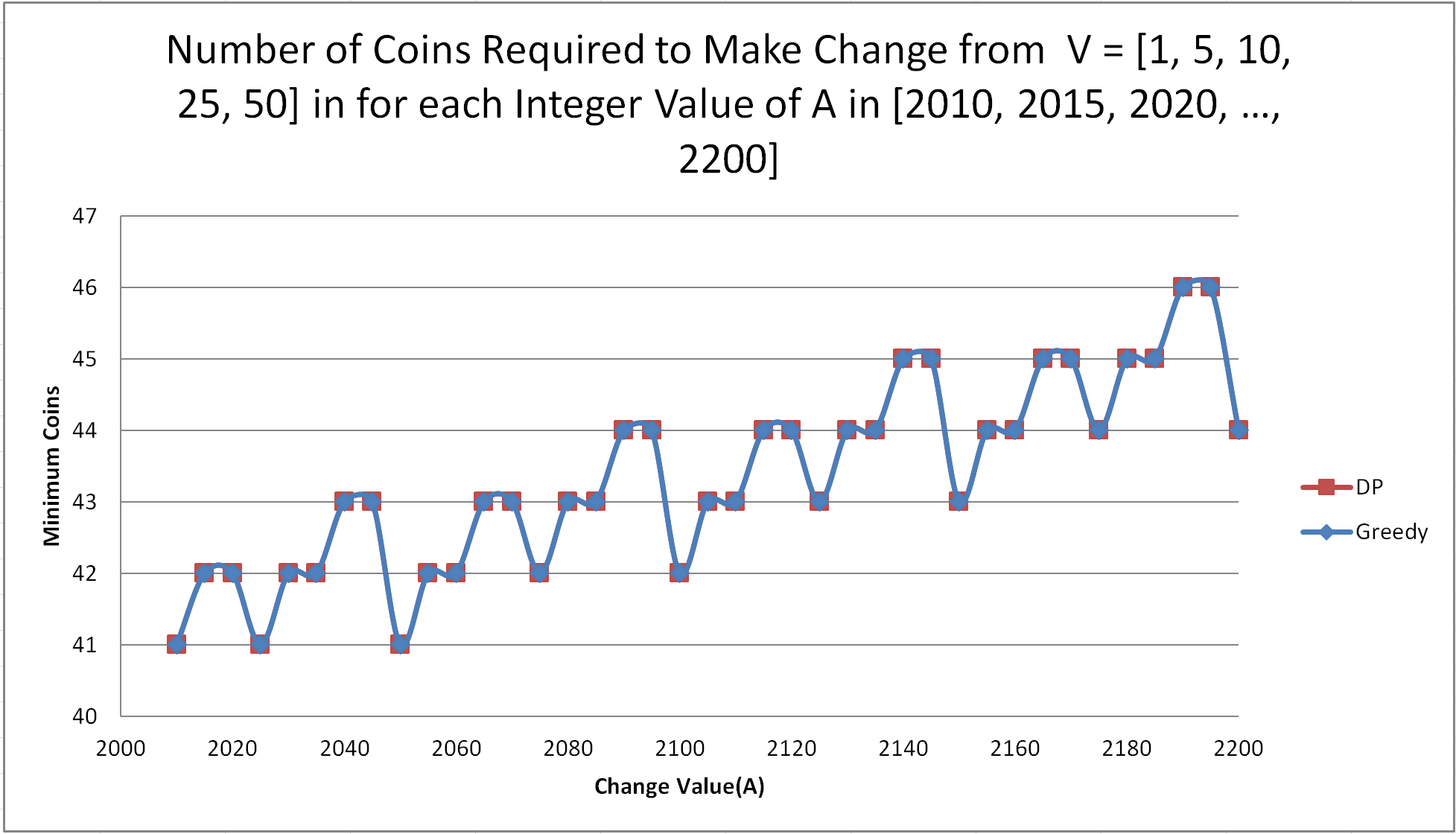
}

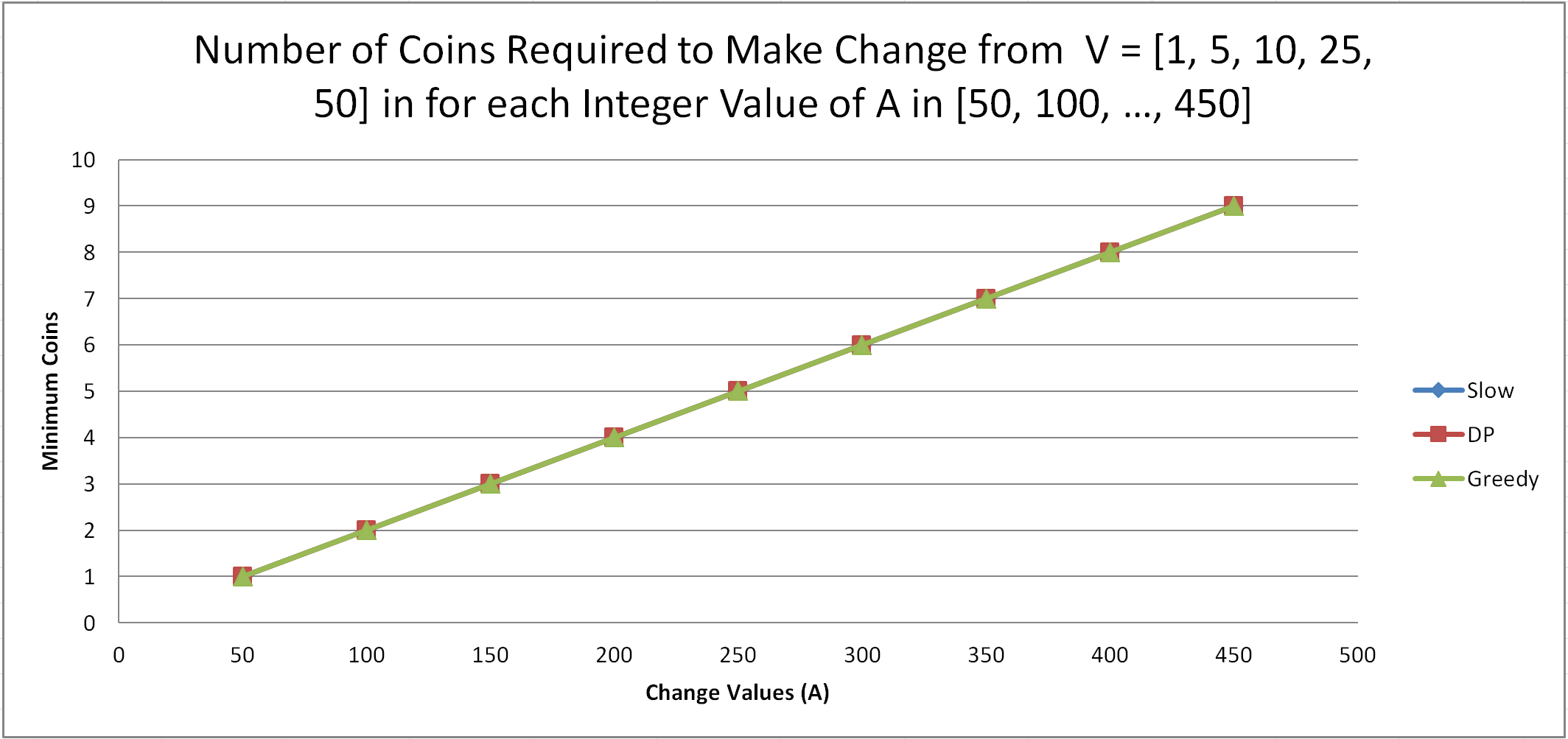
3.



4

For A of [2010, 2015, 2020, …, 2200] and V equal to [1, 5, 10, 25, 50], changegreedy and changedp returned the same minimum number of coins needed to make change for each value of A.

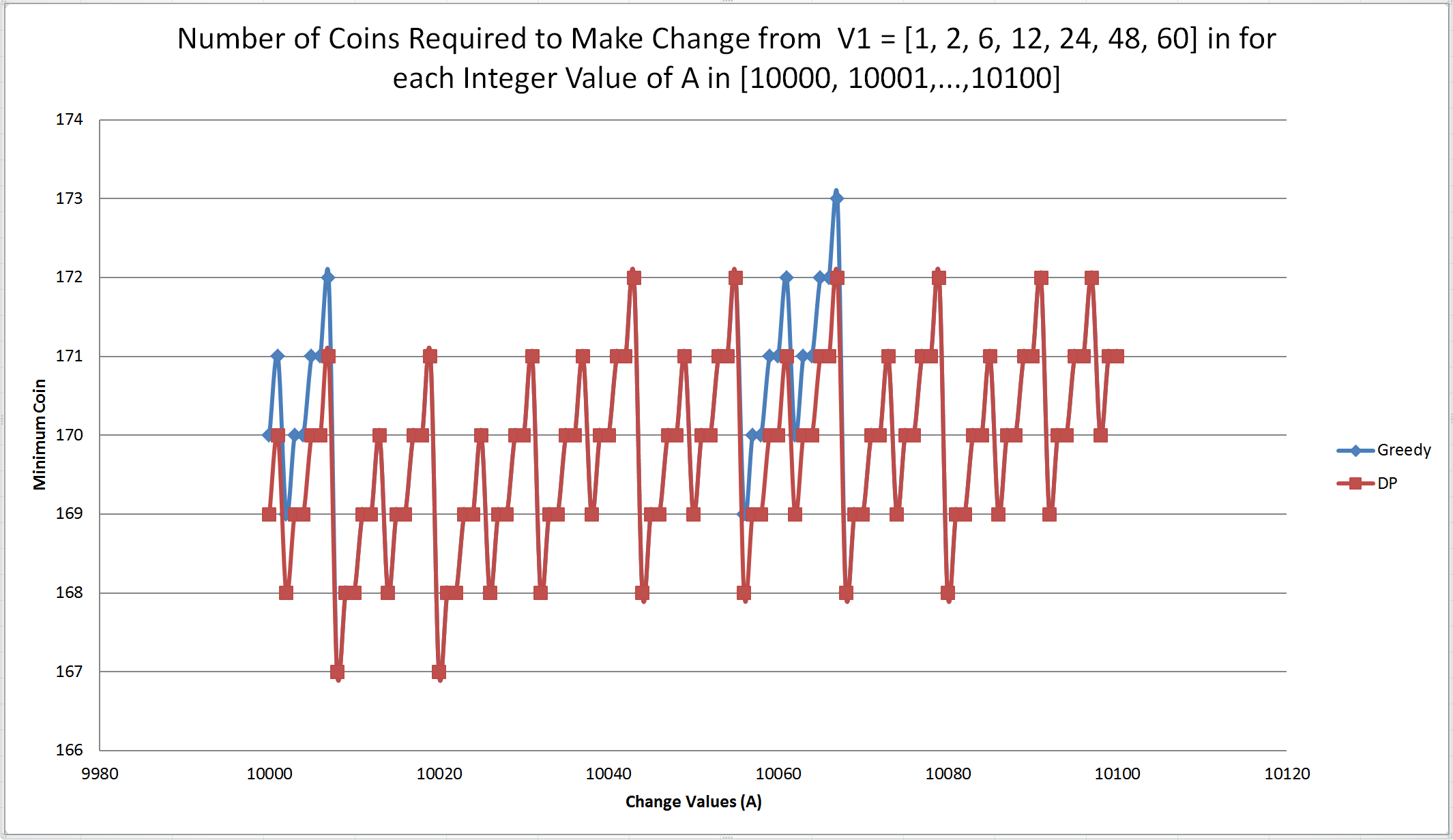


The largest A completable in a reasonable amount of time for changeslow was 450 for V of [1, 5, 10, 25, 50]. For A of [50, 100, …, 450] and V equal to [1, 5, 10, 25, 50], changeslow, changegreedy and changedp returned the same minimum number of coins needed to make change for each value of A. 

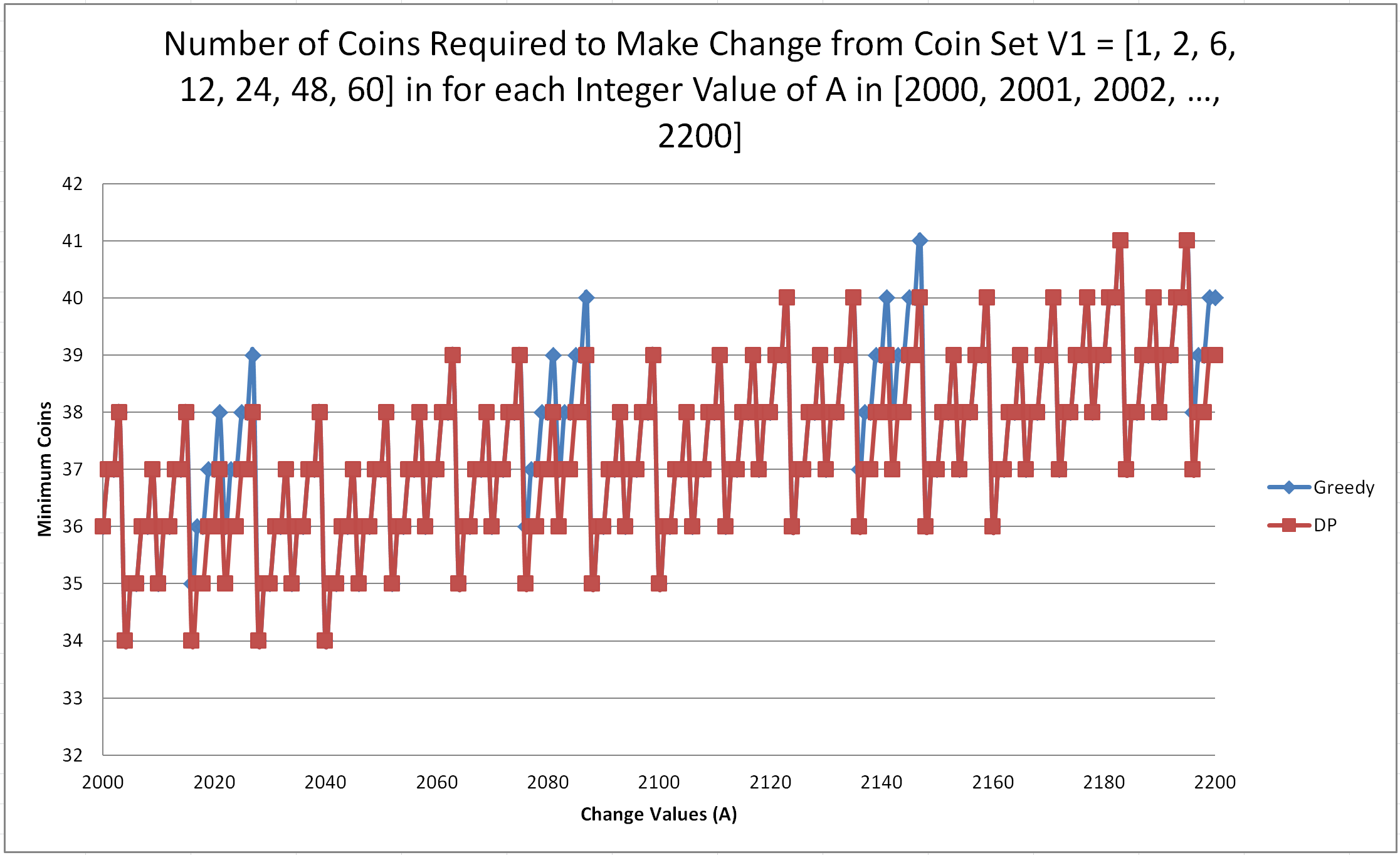
5.

a)

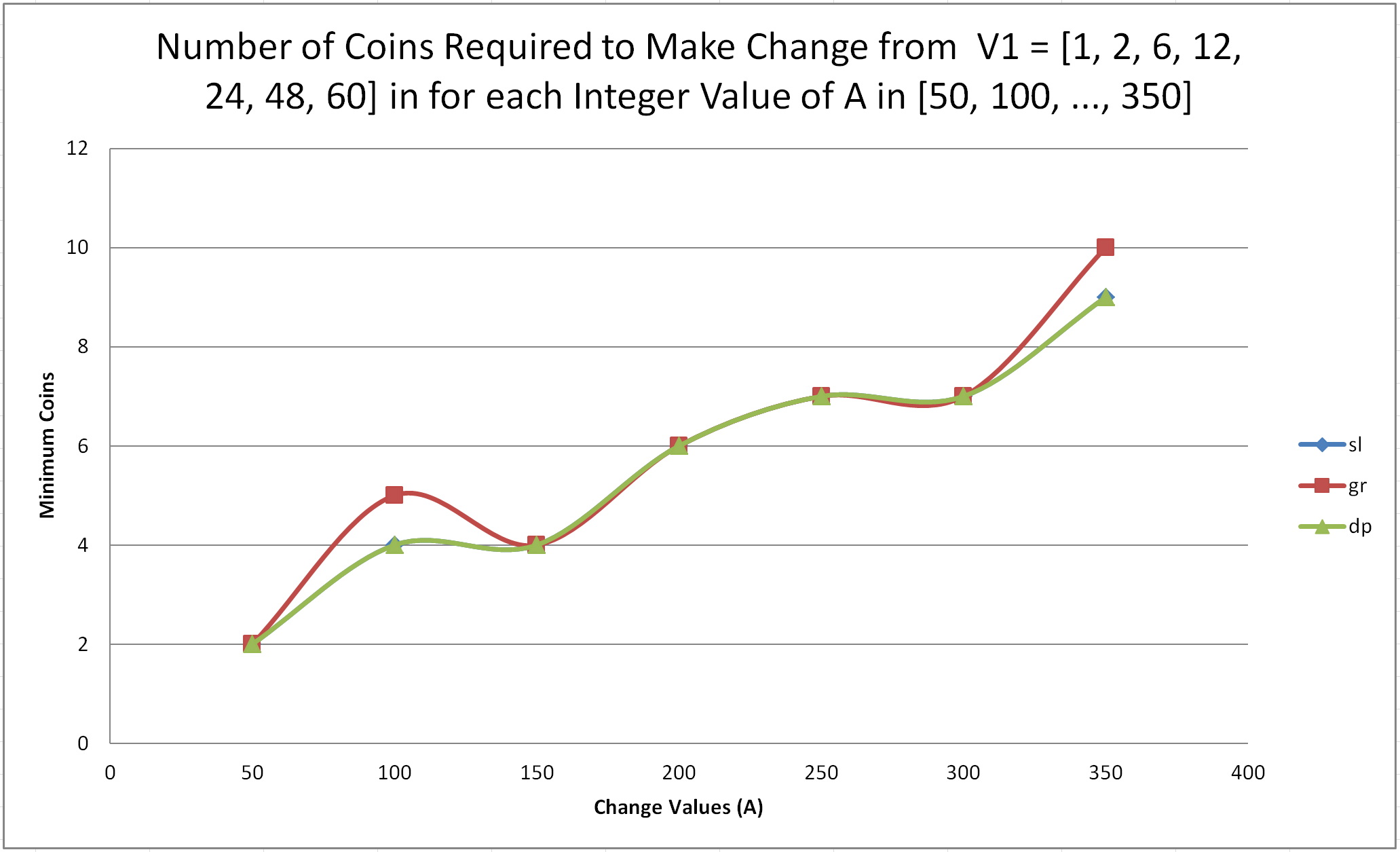
For A of [10000, 10001, …, 10100] and V1 = [1, 2, 6, 12, 24, 48, 60] changegreedy and changedp had different results for minimum number of coins required to make change for each value of A. Change Greedy does not choose the optimal solution for values such as from A in [10000, …., 10007] and A in [10057, …., 10067] in this trial for V1 = [1, 2, 6, 12, 24, 48, 60]. So the greedy algorithm will choose suboptimal solution for about 10 consecutive values of A every interval of around 60. This makes sense because the greedy algorithm can choose too many of the largest coin denominations, which is not present in the optimal solution. The greedy algorithm consistently makes this mistake periodically.



For A of [2000,2001, …, 2200] and V1 = [1, 2, 6, 12, 24, 48, 60] changegreedy does not choose the optimal solution for values such as from A in [2016, …., 2027] and afterwards from A in [2027, …, 2077] it picks the optimal solution in this trial for V1 = [1, 2, 6, 12, 24, 48, 60]. Notice the data sets for A in 2000’s and 10000’s each increase by 1. So the greedy algorithm will choose suboptimal solution for about 10 consecutive values of A every interval of around 60 for V1 = [1, 2, 6, 12, 24, 48, 60] regardless of data set A when each term in A is increasing by 1. Looking at the data in V1, it is increasing by 1, then 4, then 6 and since the set is not condensed the algorithms do not produce same results.

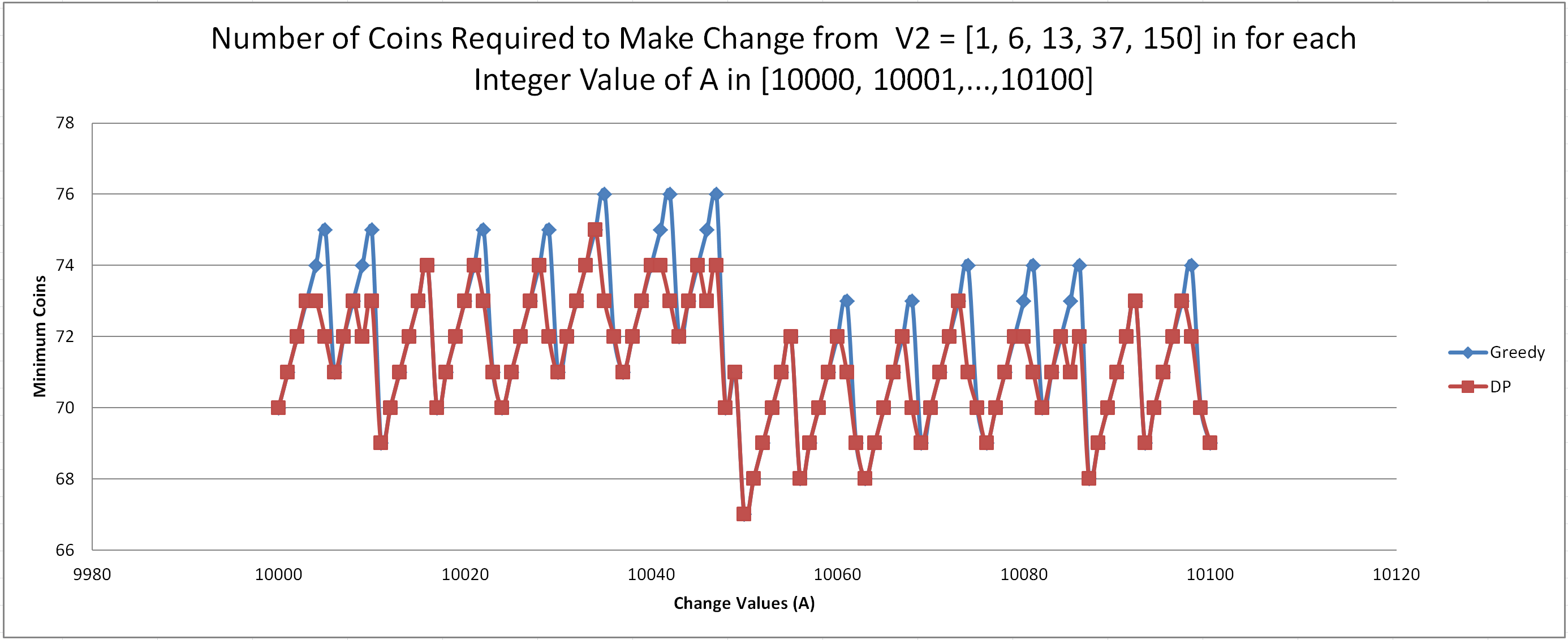


For A of [50,100, …, 350] and V1 = [1, 2, 6, 12, 24, 48, 60] we see that changeslow and changedp are the return the same values but changegreedy does not always choose the optimal solution. Here we see for values such as from A in [50, …, 150] and [300, …, 400] that greedy algorithm will choose suboptimal solution for about 100 consecutive values of A every interval of around 150. So again the greedy algorithm is periodically picking the suboptimal solutions, except with different intervals and different ranges for various sets of A.

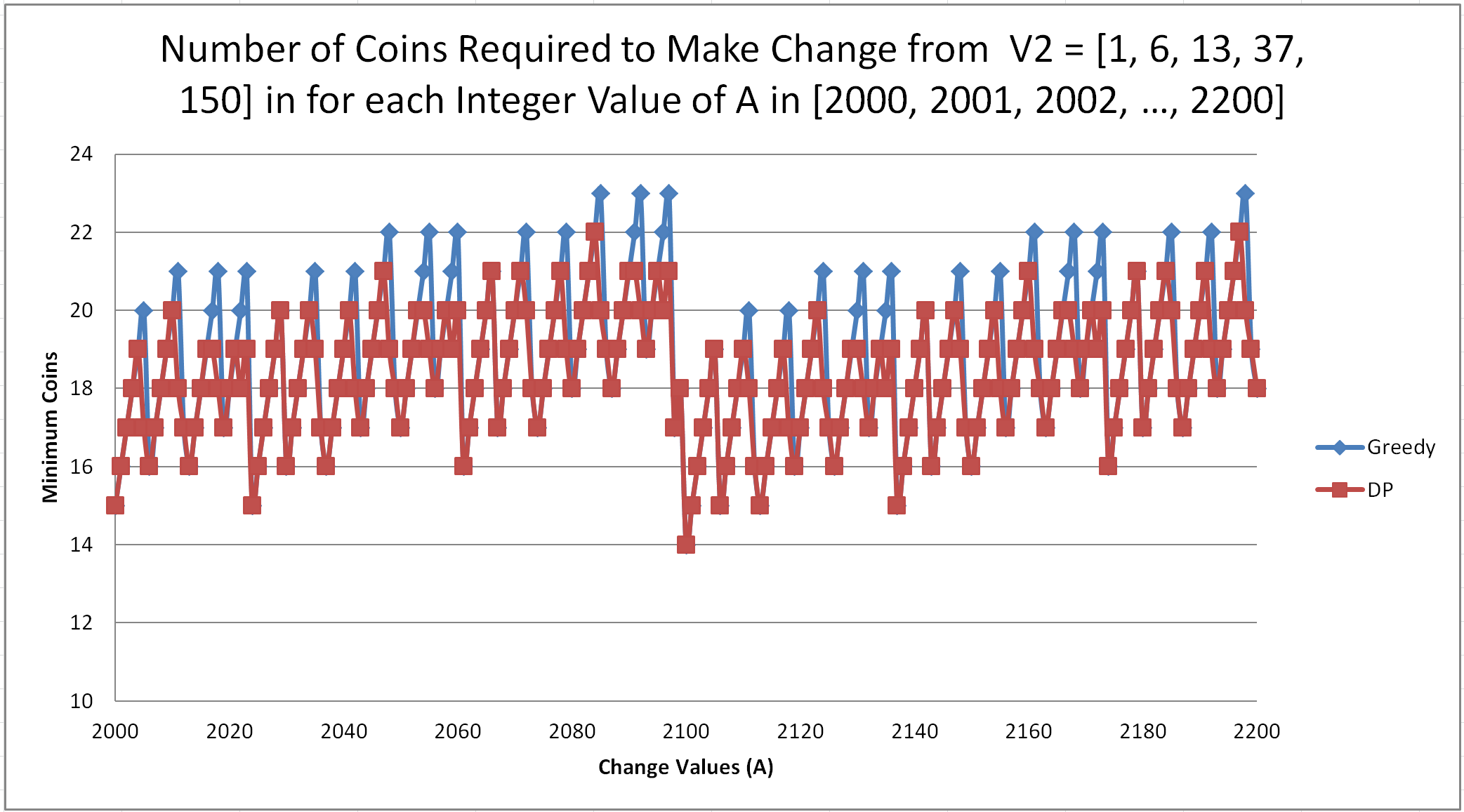


b)

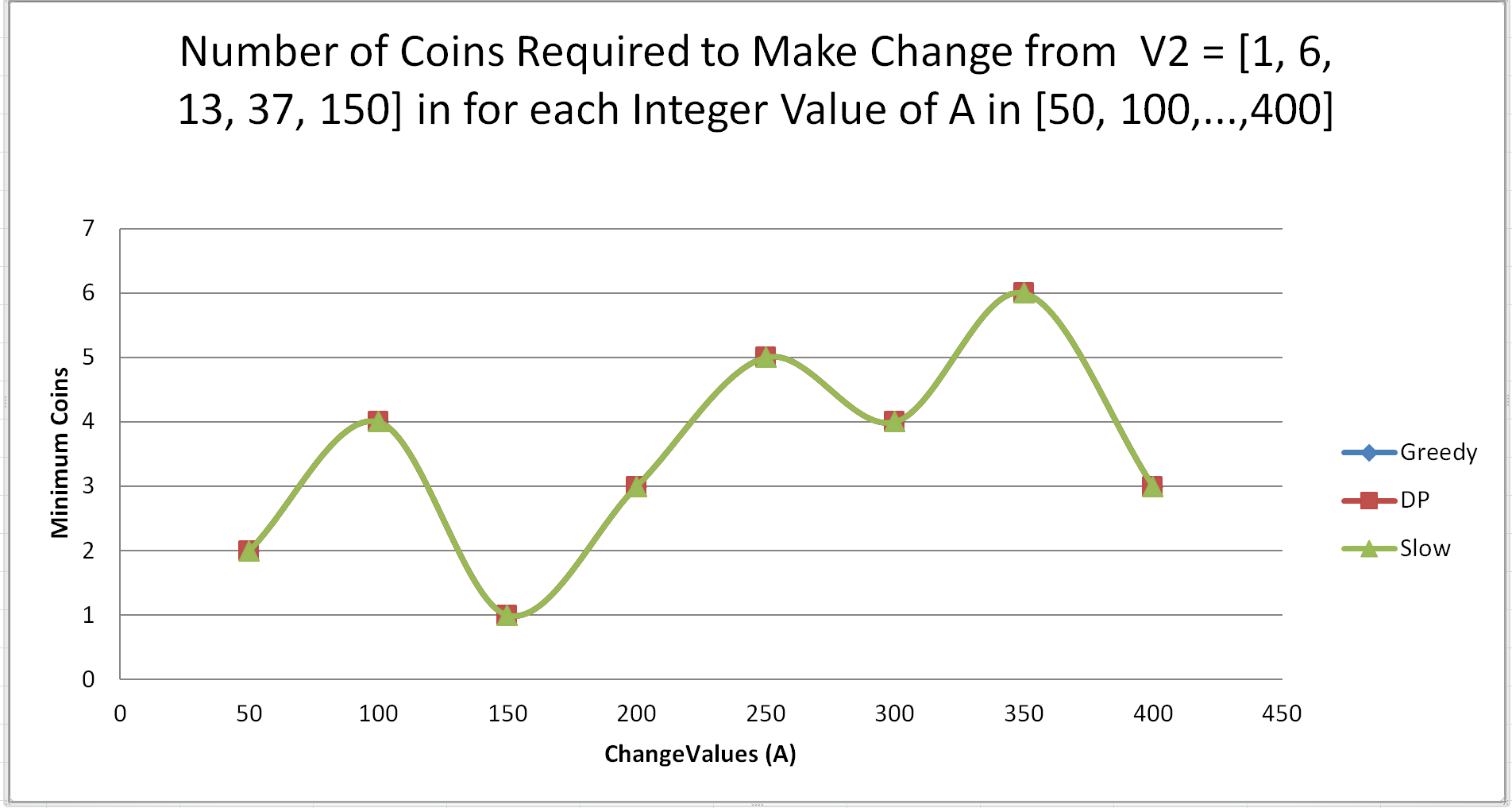
For A of [10000, 10001, …, 10100] and V2 = [1, 6, 13, 37, 150] changegreedy and changedp had different results for minimum number of coins required to make change for each value of A. Change Greedy does not choose the optimal solution for values such as from A in [10003, …., 10005], picks the optimal solution from [10005, …, 10008] then from [10008, …., 10010] goes back to picking the incorrect solution. It continues this up and down pattern five times before embarking on a ~27 A value streak where it picks the optimal solution such as for A in [10021, …., 10023], in [10028, …., 10030] in this trial. So there’s a period of around 10 A’s where there are five peaks of greedy algorithm picking suboptimal then optimal solution, then around 27 A’s where greedy picks the optimal solution each time – this is a pattern. Again the greedy algorithm is periodically picking the suboptimal solutions, except with different intervals and different ranges for various sets of A.



For A of [2000,2001, …, 2200] and V2 = [1, 6, 13, 37, 150] changegreedy does not choose the optimal solution for values such as from A in [2004, …., 2006], picks optimal solutiuon for A in [2006, …, 2010] , and proceeds to pick suboptimal solution over next 2 values of A and then optimal solution for next 4 values of A. It proceeds with five of these peaks until a long stretch of around 10 A’s where it picks optimal solution such as from A in [2023, …, 2034]. Notice this is the exact same trend as when A’s were in the 10,000s – probably because both data sets were increasing by 1 each time and V2 data is increasing by 5, then 7, then 24 and since the set is not condensed the algorithms do not produce same results.

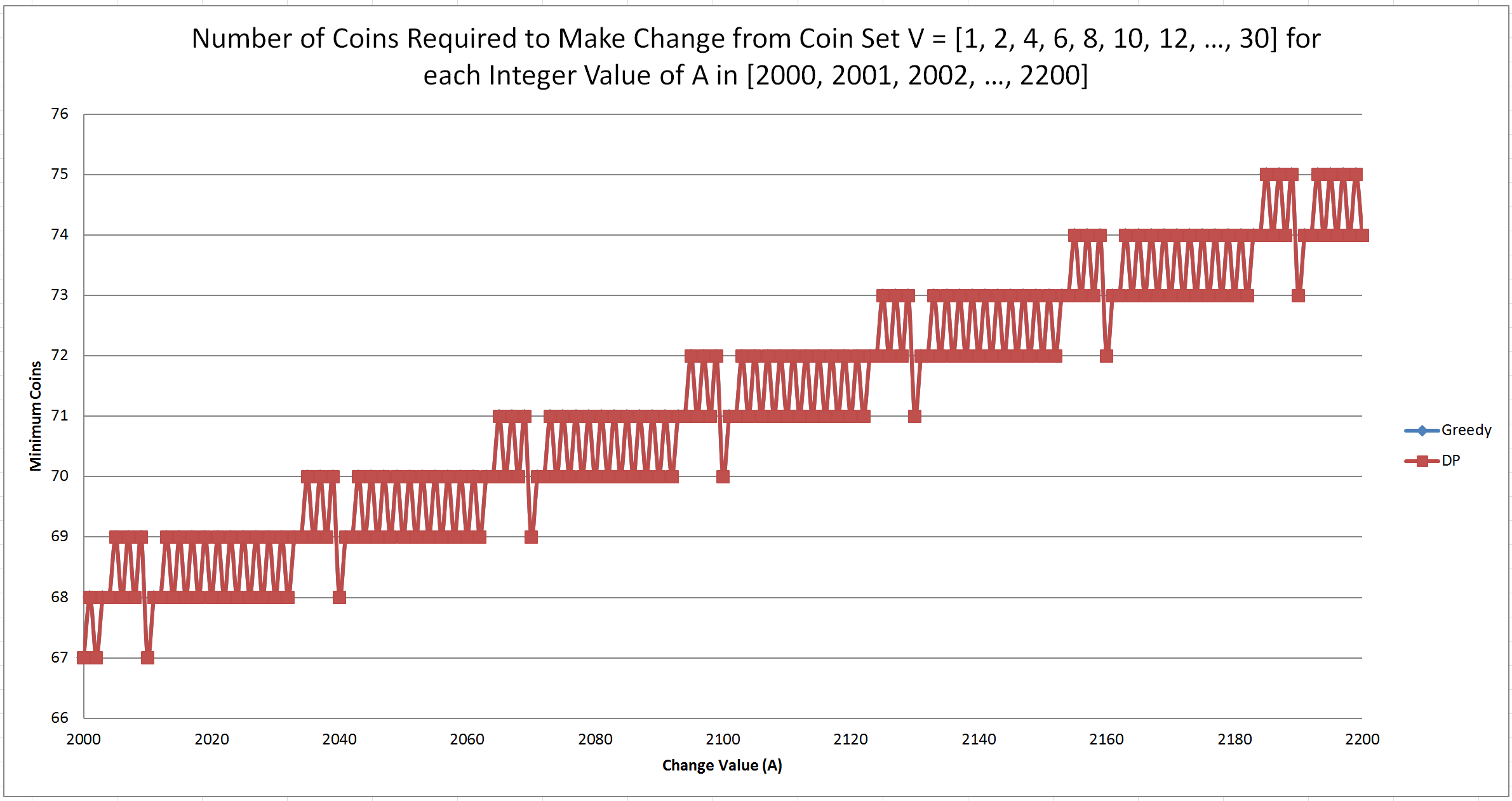


In this chart, the changeslow, changegreedy and changedp returned the same minimum number of coins needed to make change for each value of A for small values of A in [50, 100, …400] showing that for some coin sets and change values the greedy algorithm can provide the optimal solution. It just does not do it consistently but it works for this very small data set.

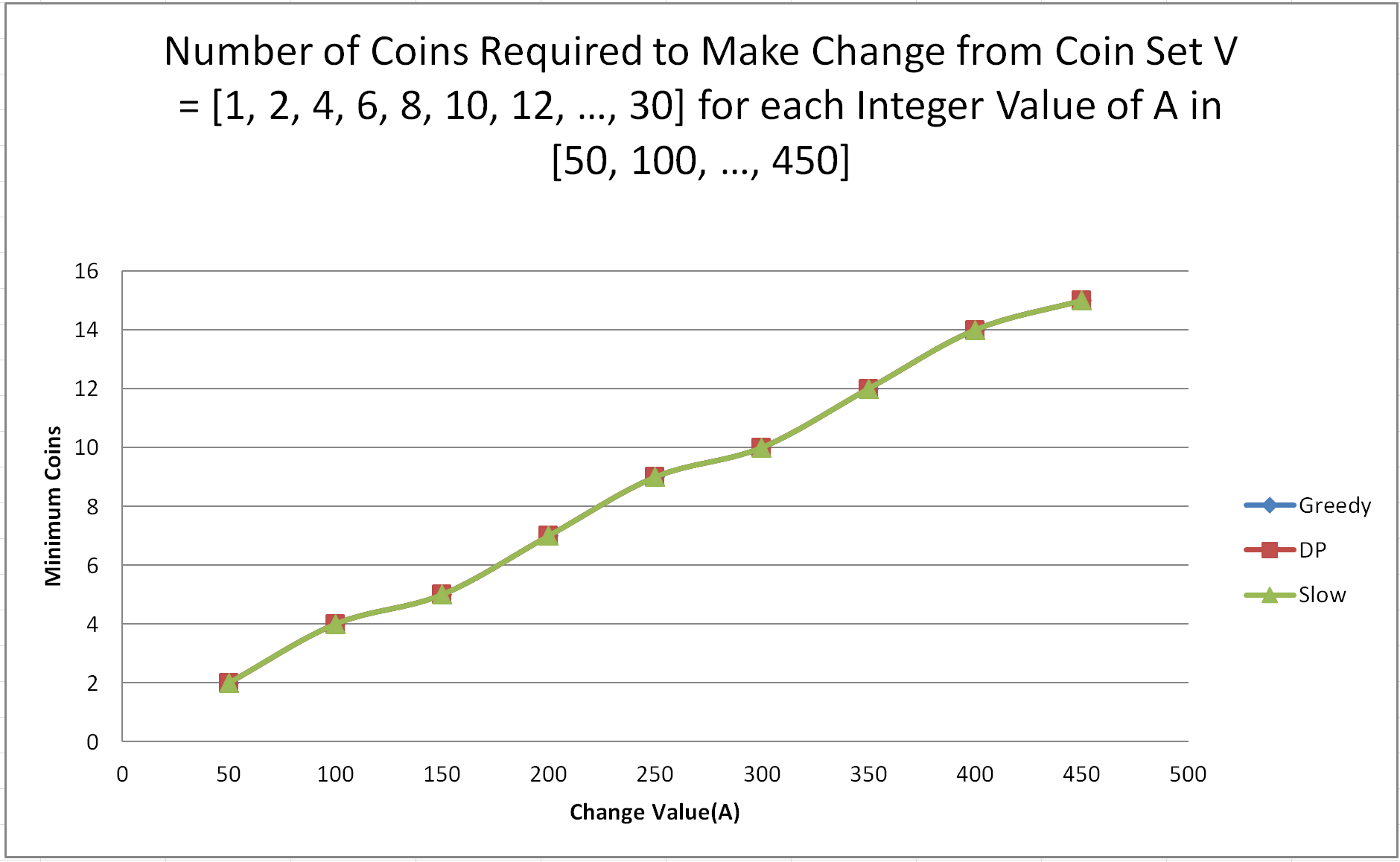


6.

For A of [2000, 2001, 2002, …, 2200] and V = [1, 2, 4, 6, 8, 10, 12, …, 30] changegreedy and changedp had same results for minimum number of coins required to make change for each value of A. This may be due to the fact that numbers in V are much more condensed than in other data sets (only increase from 1-2 consecutively), rather than in other sets where each number varies around the range of 5-20. This denseness of data may cause results for algorithms to be the same.



In this chart, the changeslow, changegreedy and changedp returned the same minimum number of coins needed to make change for each value of A for small values of A in [50, 100, …450] showing that for some coin sets (like ones where values are close together) and change values the greedy algorithm can provide the optimal solution. It just does not do it consistently but it works for this very small data set.



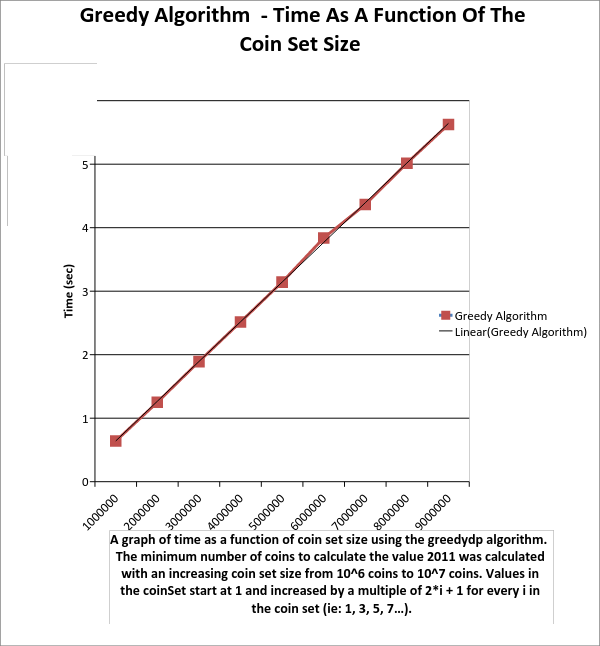
7.

The greedy algorithm is by far the most efficient being 11 orders of magnitude more efficient than the dynamic program, which is Θ(AV). The greedy algorithm is supposed to be Θ(N) where N is some number less than A. Still, the magnitude of difference between the two algorithms should not be so big according to the theoretical assumptions of this test. I think that there is something else going on with the implementations with the algorithms resulting in such a wide difference in performance. Both greedy and dynamic programs seem to follow a linear form in relation to the size of A.

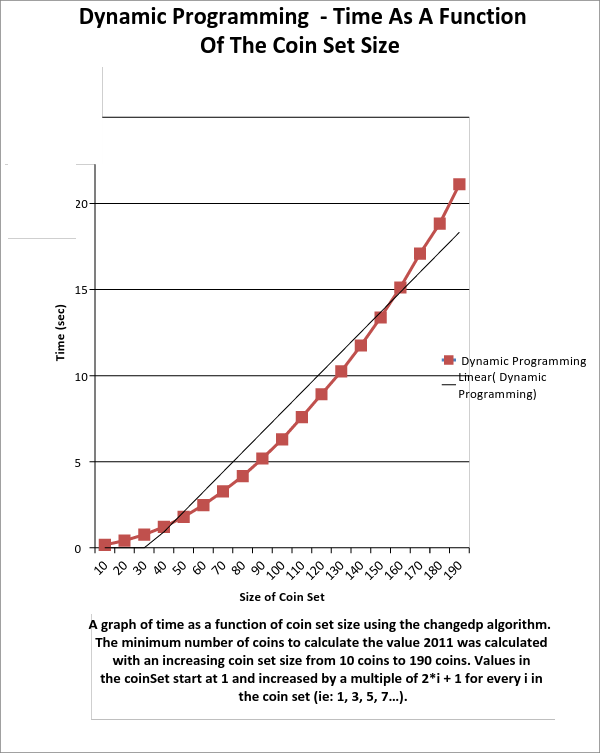
The running times of the brute force algorithm depends highly upon the size of the coinset, V. The point of inflection, where the running times quickly reach infinite, occurs much earlier when there are more than 5 coin values in set V at A = 40. The point of inflection for 5 or less coin values in set V is around 60.

8.

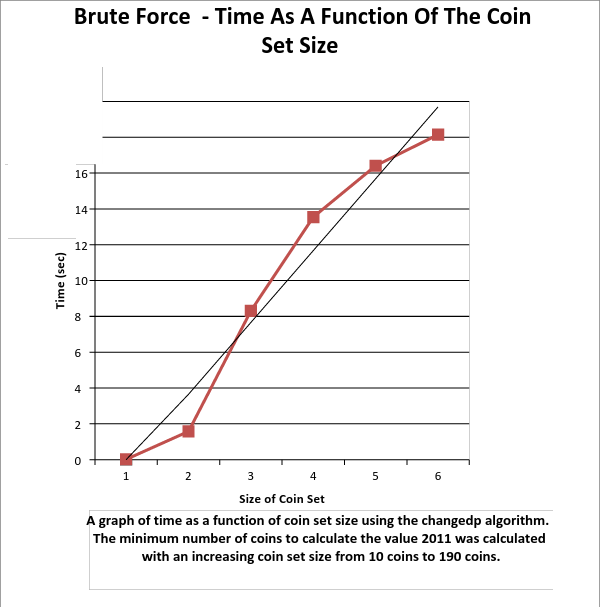
Use the data from questions 4-6 and any new data you have generated.  Plot running times as a function of number of denominations (i.e. V=[1, 10, 25, 50] has four different denominations so n=4).  Does the size of n influence the running times of any of the algorithms?



For the graph Greedy Algorithm – Time As A Function of Coin Set Size it is shown that the run time increases linearly with the size of the coin set size.   This makes sense because the greedy algorithm works by repeatedly iterating through the coin set and subtracting the largest value in the coin set that is <= to the remaining V from V.  So as the coin set grows the time to iterate through the set grows linearly.  This linear relationship is dependent on the situation when the coinset values get larger than the value V to make change for, the algorithm does not breaking out of the loop when it realizes V is less than the remaining coins in the coin set.



For the graph Dynamic Programming – Time As A Function of Coin Set Size it is shown that the run time increases quadratically as the size of the coin set size increases.  This also make sense because the changedp algorithm works be iterating through the coin set once for every value of V (value to make change for).  If n is the total time to run the algorithm then  n = (coinSet.size) x (V) + C.  Since V in the graph above is 2011 then it is always larger than the sizes of the coin sets tested, which produced the quadratic curve.  However once the coin set size get much larger than V then the runtime will depend more on the coin set size and produce a linear graph.



For the graph Brute Force – Time As A Function of Coin Set Size it is shown that the run time increases as a cubic polynomial function as the size of the coin set size increases.  The recursive brute force algorithm works by finding every result that produces a valid solution to the problem and then comparing that solution to the best solution found so far.  The time the algorithm can finish the problem in is related to the number of recursive calls needed to solve the problem.  The recursion works by iterating through the coin set and recursively calling the function again for V- coin if the coin <= V.  Which gives a recursion relation of T(n) = coinSetSize \* T(n - coins ).  So as the coin values approach the value of V then fewer recursive calls are made to solve the problem.  As the size of the coins set increases then normally the values of the coin get larger, and the function performs better as the coin values approach V.  If V is always much larger than the coin values then the extra coins in the coin set will dramatically slow down the algorithm since the number of recursive calls made is directly related to the coinSetSize, and the coinValues will not reduce the size of n very quickly, which gives exponential runtime.

9. Suppose you are living in a country where coins have values that are powers of p,   V = [1, 3, 9, 27]. How do you think the dynamic programming and greedy approaches would compare? Explain.

Since the values in the set share a greatest common factor, which is 3 and each higher value is a product of 3 \* a lower value, then the greedy algorithm will give the correct min value to make change for any value of V.  The dynamic programming  algorithm will also always give the correct solution to the problem but will run much slower than the greedy algorithm.  For this set of coins it would be better to use the greedy algorithm.

10.  Under what conditions does the greedy algorithm produce an optimal solution? Explain.

The greedy algorithm is the optimal solution to the coin change problem when the set of coins is such that any greater coin in the set can be produced by some number x times a lower value coin .  For example the coin set {1, 5, 15, 30} 1 x 5 = 5, 1 x 15 = 15 1 x 30 = 30, 3 x 5 = 5, 6 x 5 = 30, 2 x 15 = 30.  There no quicker solution to make change for a value greater the 30 that doesn’t use the 30 cent piece.  However for the coin set {1, 3, 9 , 15} 15/9 does not produce a integer, which means the greedy algorithm is not a valid solution for all values of V.