

COMP9414 Artificial Intelligence

Assignment 1: Constraint Satisfaction Search

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Due Date: Week 5, Friday, October 17, 5.00pm

Objective

This assignment concerns developing optimal solutions to a scheduling problem inspired by the scenario of a manufacturing plant that has to fulfil multiple customer orders with varying deadlines, but where there may be constraints on tasks and on relationships between tasks. Any number of tasks can be scheduled at the same time, but it is possible that some tasks cannot be finished before their deadline. A task finishing late is acceptable, however incurs a cost, which for this assignment is a simple (dollar) amount per hour that the task is late.

A *fuzzy scheduling* problem in this scenario is simplified by ignoring customer orders and having just one machine and a number of *tasks*, each with a fixed duration in hours. Each task must start and finish on the same day, within working hours (9am to 5pm). In addition, there can be *constraints*, both on single tasks and between two tasks. One type of constraint is that a task can have a deadline, which can be “hard” (the deadline must be met in any valid schedule) or “soft” (the task may be finished late – though still at or before 5pm – but with a “cost” per hour for missing the deadline). The aim is to develop an overall schedule for all the tasks (in a single week) that minimizes the total cost of all the tasks that finish late, provided that all the hard constraints on tasks are satisfied.

More technically, this assignment is an example of a *constraint optimization problem* (or *constrained optimization problem*), a problem that has constraints like a standard Constraint Satisfaction Problem (CSP), but also a *cost* associated with each solution. For this assignment, we will use a *greedy* algorithm to find optimal solutions to fuzzy scheduling problems that are specified as text strings. However, unlike the greedy search algorithm described in the lectures on search, this greedy algorithm has the property that it is guaranteed to find an optimal solution for any problem (if a solution exists).

The assignment will use the AI^{Python} code of Poole & Mackworth. You are given code to translate fuzzy scheduling problems specified as text strings into CSPs with a cost, and you are given code for several constraint solving algorithms – based on domain splitting and arc consistency, and based on depth-first search. The assignment will be to implement some missing procedures and to analyse the performance of the constraint solving methods, both analytically and experimentally.

Submission Instructions

- This is an individual assignment.
- Write your answers in **this** notebook and submit **this** notebook on Moodle under **Assignment 1**.
- Name your submission `<zid>-<firstname>-<lastname>.ipynb` where `<firstname>-<lastname>` is your **real** (not Moodle) name.
- Make sure you set up AI Python (as done below) so the code can be run on either CSE machines or a marker's own machine.
- Do not submit any AI Python code. Hence do not change any AI Python code to make your code run.
- Make sure your notebook runs cleanly (restart the kernel, clear all outputs and run each cell to check).
- After checking that your notebook runs cleanly, run all cells and submit the notebook **with** the outputs included (do not submit the empty version).
- Make sure images (for plots/graphs) are **included** in the notebook you submit (sometimes images are saved on your machine but are not in the notebook).
- Do not modify the existing code in this notebook except to answer the questions. Marks will be given as and where indicated.
- If you want to submit additional code (e.g. for generating plots), add that at the end of the notebook.
- **Important: Do not distribute any of this code on the Internet. This includes ChatGPT. Do not put this assignment into any LLM.**

Late Penalties

Standard UNSW late penalties apply (5% of the value of the assignment per day or part day late).

Note: Unlike the CSE systems, there is no grace period on Moodle. The due date and time is 5pm **precisely** on Friday October 17.

Important: You can submit as many times as you want before the due date, but if you do submit before the due date, you cannot submit on Moodle after the due date. If you do not submit before the due date, you can submit on Moodle after the due date.

Plagiarism

Remember that ALL work submitted for this assignment must be your own work and no sharing or copying of code or answers is allowed. You may discuss the assignment with other students but must not collaborate on developing answers to the questions. You

may use code from the Internet only with suitable attribution of the source. You may not use ChatGPT or any similar software to generate any part of your explanations, evaluations or code. Do not use public code repositories on sites such as github or file sharing sites such as Google Drive to save any part of your work – make sure your code repository or cloud storage is private and do not share any links. This also applies after you have finished the course, as we do not want next year's students accessing your solution, and plagiarism penalties can still apply after the course has finished.

All submitted assignments will be run through plagiarism detection software to detect similarities to other submissions, including from past years. You should **carefully** read the UNSW policy on academic integrity and plagiarism (linked from the course web page), noting, in particular, that collusion (working together on an assignment, or sharing parts of assignment solutions) is a form of plagiarism.

Finally, do not use any contract cheating “academies” or online “tutoring” services. This counts as serious misconduct with heavy penalties up to automatic failure of the course with 0 marks, and expulsion from the university for repeat offenders.

Fuzzy Scheduling

A CSP for this assignment is a set of variables representing tasks, binary constraints on pairs of tasks, and unary constraints (hard or soft) on tasks. The domains are all the working hours in one week, and a task duration is in hours. Days are represented (in the input and output) as strings ‘mon’, ‘tue’, ‘wed’, ‘thu’ and ‘fri’, and times are represented as strings ‘9am’, ‘10am’, ‘11am’, ‘12pm’, ‘1pm’, ‘2pm’, ‘3pm’, ‘4pm’ and ‘5pm’. The only possible values for the start and end times of a task are combinations of a day and times, e.g. ‘mon 9am’. Each task name is a string (with no spaces), and the only soft constraints are the soft deadline constraints.

There are three types of constraint:

- **Binary Constraints:** These specify a hard requirement for the relationship between two tasks.
- **Hard Domain Constraints:** These specify hard requirements for the tasks themselves.
- **Soft Deadline Constraints:** These constraints specify that a task may finish late, but with a given cost.

Each soft constraint has a function defining the *cost* associated with violating the preference, that the constraint solver must minimize, while respecting all the hard constraints. The *cost* of a solution is simply the sum of the costs for the soft constraints that the solution violates (and is always a non-negative integer).

This is the list of possible constraints for a fuzzy scheduling problem (comments below are for explanation and do **not** appear in the input specification; however, the code we supply *should* work with comments that take up a full line):

```

# binary constraints
constraint, <t1> before <t2>                      # t1 ends when or before
t2 starts
constraint, <t1> after <t2>                         # t1 starts after or when
t2 ends
constraint, <t1> same-day <t2>                      # t1 and t2 are scheduled
on the same day
constraint, <t1> starts-at <t2>                     # t1 starts exactly when
t2 ends

# hard domain constraints
domain, <t>, <day>, hard                           # t
starts on given day at any time
domain, <t>, <time>, hard                            # t
starts at given time on any day
domain, <t>, starts-before <day> <time>, hard      # t
starts at or before day, time
domain, <t>, starts-after <day> <time>, hard        # t
starts at or after day, time
domain, <t>, ends-before <day> <time>, hard         # t
ends at or before day, time
domain, <t>, ends-after <day> <time>, hard          # t
starts at or after day, time
domain, <t>, starts-in <day1> <time1>-<day2> <time2>, hard # day-
time range for start time; includes day1, time1 and day2, time2
domain, <t>, ends-in <day1> <time1>-<day2> <time2>, hard   # day-
time range for end time; includes day1, time1 and day2, time2
domain, <t>, starts-before <time>, hard              # t
starts at or before time on any day
domain, <t>, ends-before <time>, hard                # t
ends at or before time on any day
domain, <t>, starts-after <time>, hard              # t
starts at or after time on any day
domain, <t>, ends-after <time>, hard                # t
ends at or after time on any day

# soft deadline constraint
domain, <t>, ends-by <day> <time> <cost>, soft      # cost per
hour of missing deadline

```

The input specification will consist of several “blocks”, listing the tasks, binary constraints, hard unary constraints and soft deadline constraints for the given problem. A “declaration” of each task will be included before it is used in a constraint. A sample input specification is as follows. Comments are for explanation and do **not** have to be included in the input.

```

# two tasks with two binary constraints and soft deadlines
task, t1 3
task, t2 4
# two binary constraints
constraint, t1 before t2
constraint, t1 same-day t2
# domain constraint
domain, t2 mon

```

```
# soft deadline constraints  
domain, t1 ends-by mon 3pm 10  
domain, t2 ends-by mon 3pm 10
```

Preparation

1. Set up AlPython

You will need AlPython for this assignment. To find the aipython files, the aipython directory has to be added to the Python path.

Do this temporarily, as done here, so we can find AlPython and run your code (you will not submit any AlPython code).

You can add either the full path (using `os.path.abspath()`), or as in the code below, the relative path.

In [306...]

```
import sys  
sys.path.append('C:/Files/Course/COMP9414/aipython') # change to your directory  
sys.path # check that aipython is now on the path
```

Out[306...]

```
['c:\\\\Files\\\\Course\\\\COMP9414',  
 'c:\\\\Users\\\\Ramb1\\\\anaconda3\\\\python312.zip',  
 'c:\\\\Users\\\\Ramb1\\\\anaconda3\\\\DLLs',  
 'c:\\\\Users\\\\Ramb1\\\\anaconda3\\\\Lib',  
 'c:\\\\Users\\\\Ramb1\\\\anaconda3',  
 '',  
 'c:\\\\Users\\\\Ramb1\\\\anaconda3\\\\Lib\\\\site-packages',  
 'c:\\\\Users\\\\Ramb1\\\\anaconda3\\\\Lib\\\\site-packages\\\\win32',  
 'c:\\\\Users\\\\Ramb1\\\\anaconda3\\\\Lib\\\\site-packages\\\\win32\\\\lib',  
 'c:\\\\Users\\\\Ramb1\\\\anaconda3\\\\Lib\\\\site-packages\\\\Pythonwin',  
 'C:/Files/Course/COMP9414/aipython',  
 'C:/Files/Course/COMP9414/aipython']
```

2. Representation of Day Times

Input and output are day time strings such as 'mon 10am' or a range of day time strings such as 'mon 10am-mon 4pm'.

The CSP will represent these as integer hour numbers in the week, ranging from 0 to 39.

The following code handles the conversion between day time strings and hour numbers.

In [307...]

```
# -*- coding: utf-8 -*-

""" day_time string format is a day plus time, e.g. Mon 10am, Tue 4pm, or just T
if only day or time, returns day number or hour number only
day_time strings are converted to and from integer hours in the week from 0
"""

class Day_Time():
    num_hours_in_day = 8
    num_days_in_week = 5

    def __init__(self):
        self.day_names = ['mon','tue','wed','thu','fri']
        self.time_names = ['9am','10am','11am','12pm','1pm','2pm','3pm','4pm']

    def string_to_week_hour_number(self, day_time_str):
        """ convert a single day_time into an integer hour in the week """
        value = None
        value_type = None
        day_time_list = day_time_str.split()
        if len(day_time_list) == 1:
            str1 = day_time_list[0].strip()
            if str1 in self.time_names: # this is a time
                value = self.time_names.index(str1)
                value_type = 'hour_number'
            else:
                value = self.day_names.index(str1) # this is a day
                value_type = 'day_number'
            # if not day or time, throw an exception
        else:
            value = self.day_names.index(day_time_list[0].strip())*self.num_hours_in_day
            + self.time_names.index(day_time_list[1].strip())
            value_type = 'week_hour_number'
        return (value_type, value)

    def string_to_number_set(self, day_time_list_str):
        """ convert a list of day-times or ranges 'Mon 9am, Tue 9am-Tue 4pm' int
        e.g. 'mon 9am-1pm, mon 4pm' -> [0,1,2,3,4,7]
        """
        number_set = set()
        type1 = None
        for str1 in day_time_list_str.lower().split(','):
            if str1.find('-') > 0:
                # day time range
                type1, v1 = self.string_to_week_hour_number(str1.split('-')[0])
                type2, v2 = self.string_to_week_hour_number(str1.split('-')[1])
                if type1 != type2: return None # error, types in range spec are
                number_set.update({n for n in range(v1, v2+1)})
            else:
                # single day time
                type2, value2 = self.string_to_week_hour_number(str1)
                if type1 != None and type1 != type2: return None # error: type i
                type1 = type2
                number_set.update({value2})
        return (type1, number_set)

    # convert integer hour in week to day time string
    def week_hour_number_to_day_time(self, week_hour_number):
        hour = self.day_hour_number(week_hour_number)
        day = self.day_number(week_hour_number)
```

```

    return self.day_names[day] + ' ' + self.time_names[hour]

# convert integer hour in week to integer day and integer time in day
def hour_day_split(self, week_hour_number):
    return (self.day_hour_number(week_hour_number), self.day_number(week_hou

# convert integer hour in week to integer day in week
def day_number(self, week_hour_number):
    return int(week_hour_number / self.num_hours_in_day)

# convert integer hour in week to integer time in day
def day_hour_number(self, week_hour_number):
    return week_hour_number % self.num_hours_in_day

def __repr__(self):
    day_hour_number = self.week_hour_number % self.num_hours_in_day
    day_number = int(self.week_hour_number / self.num_hours_in_day)
    return self.day_names[day_number] + ' ' + self.time_names[day_hour_number]

```

3. Constraint Satisfaction Problems with Costs over Tasks with Durations

Since AI Python does not provide the CSP class with an explicit cost, we implement our own class that extends `CSP`.

We also store the cost functions and the durations of all tasks explicitly in the CSP.

The durations of the tasks are used in the `hold` function to evaluate constraints.

In [308...]

```

from cspProblem import CSP, Constraint

# We need to override Constraint, because tasks have durations
class Task_Constraint(Constraint):
    """A Task_Constraint consists of
    * scope: a tuple of variables
    * spec: text description of the constraint used in debugging
    * condition: a function that can applied to a tuple of values for the variab
    * durations: durations of all tasks
    * func_key: index to the function used to evaluate the constraint
    """

    def __init__(self, scope, spec, condition, durations, func_key):
        super().__init__(scope, condition, spec)
        self.scope = scope
        self.condition = condition
        self.durations = durations
        self.func_key = func_key

    def holds(self, assignment):
        """returns the value of Constraint con evaluated in assignment.

        precondition: all variables are assigned in assignment
        CSP has only binary constraints
        condition is in the form week_hour_number1, week_hour_number2
        add task durations as appropriate to evaluate condition
        """
        if self.func_key == 'before':
            # t1 ends before t2 starts, so we need add duration to t1 assignment

```

```

        ass0 = assignment[self.scope[0]] + self.durations[self.scope[0]]
        ass1 = assignment[self.scope[1]]
    elif self.func_key == 'after':
        # t2 ends before t1 starts so we need add duration to t2 assignment
        ass0 = assignment[self.scope[0]]
        ass1 = assignment[self.scope[1]] + self.durations[self.scope[1]]
    elif self.func_key == 'starts-at':
        # t1 starts exactly when t2 ends, so we need add duration to t2 assi
        ass0 = assignment[self.scope[0]]
        ass1 = assignment[self.scope[1]] + self.durations[self.scope[1]]
    else:
        return self.condition(*tuple(assignment[v] for v in self.scope))
    # condition here comes from get_binary_constraint
    return self.condition(*tuple([ass0, ass1]))

# implement nodes as CSP problems with cost functions
class CSP_with_Cost(CSP):
    """ cost_functions maps a CSP var, here a task name, to a list of functions
    """
    def __init__(self, domains, durations, constraints, cost_functions, soft_day_time):
        self.domains = domains
        self.variables = self.domains.keys()
        super().__init__("title of csp", self.variables, constraints)
        self.durations = durations
        self.cost_functions = cost_functions
        self.soft_day_time = soft_day_time
        self.soft_costs = soft_costs
        self.cost = self.calculate_cost()

    # specific to fuzzy scheduling CSP problems
    def calculate_cost(self):
        """ calculate total cost of current assignment in domains """
        total_cost = 0
        for var in self.variables:
            if var in self.cost_functions:
                best_cost = float('inf')
                for func in self.cost_functions[var]:
                    for domain_value in self.domains[var]:
                        value_cost = func(domain_value, self.soft_day_time[var]),
                        if value_cost < best_cost:
                            best_cost = value_cost
                total_cost += best_cost
        return total_cost

    def __repr__(self):
        """ string representation of an arc"""
        return "CSP_with_Cost("+str(list(self.domains.keys()))+':'+str(self.cost)

```

This formulates a solver for a CSP with cost as a search problem, using domain splitting with arc consistency to define the successors of a node.

In [309...]:

```

def partition_domain_k(domain, k=2):

    domain = list(domain)
    n = len(domain)
    step = max(1, n // k)
    parts = []
    start = 0
    for i in range(k - 1):
        parts.append(set(domain[start:start + step]))

```

```

        start += step
parts.append(set(domain[start:]))
return [p for p in parts if p]

```

In [310...]

```

from cspConsistency import Con_solver, select, partition_domain
from searchProblem import Arc, Search_problem
from operator import eq, le, ge

# rewrites rather than extends Search_with_AC_from_CSP
class Search_with_AC_from_Cost_CSP(Search_problem):
    """ A search problem with domain splitting and arc consistency """
    def __init__(self, csp,k=2):
        self.k = k
        self.cons = Con_solver(csp) # copy of the CSP with access to arc consist
        self.domains = self.cons.make_arc_consistent(csp.domains)
        self.constraints = csp.constraints
        self.cost_functions = csp.cost_functions
        self.durations = csp.durations
        self.soft_day_time = csp.soft_day_time
        self.soft_costs = csp.soft_costs
        csp.domains = self.domains # after arc consistency
        self.csp = csp

    def is_goal(self, node):
        """ node is a goal if all domains have exactly 1 element """
        return all(len(node.domains[var]) == 1 for var in node.domains)

    def start_node(self):
        return CSP_with_Cost(self.domains, self.durations, self.constraints,
                             self.cost_functions, self.soft_day_time, self.soft_)

    def neighbors(self, node):
        """returns the neighboring nodes of node.
        """
        neights = []
        var = select(x for x in node.domains if len(node.domains[x]) > 1) # chooses
        if var:
            doms = partition_domain_k(node.domains[var], self.k)
            self.display(2, "Splitting", var, "into", doms)
            to_do = self.cons.new_to_do(var, None)
            for dom in doms:
                newdoms = node.domains | {var: dom} # overwrite domain of var with
                cons_doms = self.cons.make_arc_consistent(newdoms, to_do)
                if all(len(cons_doms[v]) > 0 for v in cons_doms):
                    # all domains are non-empty
                    # make new CSP_with_Cost node to continue the search
                    csp_node = CSP_with_Cost(cons_doms, self.durations, self.con
                                             self.cost_functions, self.soft_day_time, self.soft_
                    neights.append(Arc(node, csp_node)))
                else:
                    self.display(2, "...", var, "in", dom, "has no solution")
        return neights

    def heuristic(self, n):
        return n.cost

```

4. Fuzzy Scheduling Constraint Satisfaction Problems

The following code sets up a CSP problem from a given specification.

Hard (unary) domain constraints are applied to reduce the domains of the variables before the constraint solver runs.

In [311...]

```
# domain specific CSP builder for week schedule
class CSP_builder():
    # list of text Lines without comments and empty lines
    _, default_domain = Day_Time().string_to_number_set('mon 9am-fri 4pm') # show

    # hard unary constraints: domain is a list of values, params is a single val
    # starts-before, ends-before (for starts-before duration should be 0)
    # vals in domain are actual task start/end date/time, so must be val <= what
    def apply_before(self, param_type, params, duration, domain):
        domain_orig = domain.copy()
        param_val = params.pop()
        for val in domain_orig: # val is week_hour_number
            val1 = val + duration
            h, d = Day_Time().hour_day_split(val1)
            if param_type == 'hour_number' and h > param_val:
                if val in domain: domain.remove(val)
            if param_type == 'day_number' and d > param_val:
                if val in domain: domain.remove(val)
            if param_type == 'week_hour_number' and val1 > param_val:
                if val in domain: domain.remove(val)
        return domain

    def apply_after(self, param_type, params, duration, domain):
        domain_orig = domain.copy()
        param_val = params.pop()
        for val in domain_orig: # val is week_hour_number
            val1 = val + duration
            h, d = Day_Time().hour_day_split(val1)
            if param_type == 'hour_number' and h < param_val:
                if val in domain: domain.remove(val)
            if param_type == 'day_number' and d < param_val:
                if val in domain: domain.remove(val)
            if param_type == 'week_hour_number' and val1 < param_val:
                if val in domain: domain.remove(val)
        return domain

    # day time range only
    # includes starts-in, ends-in
    # duration is 0 for starts-in, task duration for ends-in
    def apply_in(self, params, duration, domain):
        domain_orig = domain.copy()
        for val in domain_orig: # val is week_hour_number
            # task must be within range
            if val in domain and val+duration not in params:
                domain.remove(val)
        return domain

    # task must start at day/time
    def apply_at(self, param_type, param, domain):
        domain_orig = domain.copy()
        for val in domain_orig:
            h, d = Day_Time().hour_day_split(val)
            if param_type == 'hour_number' and param != h:
```

```

        if val in domain: domain.remove(val)
    if param_type == 'day_number' and param != d:
        if val in domain: domain.remove(val)
    if param_type == 'week_hour_number' and param != val:
        if val in domain: domain.remove(val)
    return domain

# soft deadline constraints: return cost to break constraint
# ends-by implementation: domain_dt is the day, hour from the domain
# constr_dt is the soft const spec, dur is the duration of task
# soft_cost is the unit cost of completion delay
# so if the tasks starts on domain_dt, it ends on domain_dt+dur
"""
<t> ends-by <day> <time>, both must be specified
delay = day_hour(T2) - day_hour(T1) + 24*(D2 - D1),
where day_hour(9am) = 0, day_hour(5pm) = 7
"""

def ends_by(self, domain_dt, constr_dt_str, dur, soft_cost):
    param_type, params = Day_Time().string_to_number_set(constr_dt_str)
    param_val = params.pop()
    dom_h, dom_d = Day_Time().hour_day_split(domain_dt+dur)
    if param_type == 'week_hour_number':
        con_h, con_d = Day_Time().hour_day_split(param_val)
        return 0 if domain_dt + dur <= param_val else soft_cost*(dom_h - con_d)
    else:
        return None # not good, must be day and time

def no_cost(self, day, hour):
    return 0

# hard binary constraint, the rest are implemented as gt, lt, eq
def same_day(self, week_hour1, week_hour2):
    h1, d1 = Day_Time().hour_day_split(week_hour1)
    h2, d2 = Day_Time().hour_day_split(week_hour2)
    return d1 == d2

# domain is a list of values
def apply_hard_constraint(self, domain, duration, spec):
    tokens = func_key = spec.split(' ')
    if len(tokens) > 1:
        func_key = spec.split(' ')[0].strip()
    param_type, params = Day_Time().string_to_number_set(spec[len(func_key)])
    if func_key == 'starts-before':
        # duration is 0 for starts before, since we do not modify the time
        return self.apply_before(param_type, params, 0, domain)
    if func_key == 'ends-before':
        return self.apply_before(param_type, params, duration, domain)
    if func_key == 'starts-after':
        return self.apply_after(param_type, params, 0, domain)
    if func_key == 'ends-after':
        return self.apply_after(param_type, params, duration, domain)
    if func_key == 'starts-in':
        return self.apply_in(params, 0, domain)
    if func_key == 'ends-in':
        return self.apply_in(params, duration, domain)
    else:
        # here we have task day or time, it has no func key so we need to parse
        param_type, params = Day_Time().string_to_week_hour_number(spec)
        return self.apply_at(param_type, params, domain)

```

```

def get_cost_function(self, spec):
    func_dict = {'ends-by':self.ends_by, 'no-cost':self.no_cost}
    return [func_dict[spec]]

# spec is the text of a constraint, e.g. 't1 before t2'
# durations are durations of all tasks
def get_binary_constraint(self, spec, durations):
    tokens = spec.strip().split(' ')
    if len(tokens) != 3: return None # error in spec
    # task1 relation task2
    fun_dict = {'before':le, 'after':ge, 'starts-at':eq, 'same-day':self.same_day}
    return Task_Constraint((tokens[0].strip(), tokens[2].strip()), spec, fun_dict)

def get_CSP_with_Cost(self, input_lines):
    # Note: It would be more elegant to make task a class but AIpython is no longer object oriented
    # CSP_with_Cost inherits from CSP, which takes domains and constraints functions
    domains = dict()
    constraints = []
    cost_functions = dict()
    durations = dict() # durations of tasks
    soft_day_time = dict() # day time specs of soft constraints
    soft_costs = dict() # costs of soft constraints

    for input_line in input_lines:
        func_spec = None
        input_line_tokens = input_line.strip().split(',')
        if len(input_line_tokens) != 2:
            return None # must have number of tokens = 2
        line_token1 = input_line_tokens[0].strip()
        line_token2 = input_line_tokens[1].strip()
        if line_token1 == 'task':
            tokens = line_token2.split(' ')
            if len(tokens) != 2:
                return None # must have number of tokens = 3
            key = tokens[0].strip()
            # check the duration and save it
            duration = int(tokens[1].strip())
            if duration > Day_Time().num_hours_in_day:
                return None
            durations[key] = duration
            # set zero cost function for this task as default, may add real cost later
            cost_functions[key] = self.get_cost_function('no-cost')
            soft_costs[key] = '0'
            soft_day_time[key] = 'fri 5pm'
            # restrict domain to times that are within allowed range
            # that is start 9-5, start+duration in 9-5
            domains[key] = {x for x in self.default_domain \
                            if Day_Time().day_number(x+duration) \
                            == Day_Time().day_number(x)}
        elif line_token1 == 'domain':
            tokens = line_token2.split(' ')
            if len(tokens) < 2:
                return None # must have number of tokens >= 2
            key = tokens[0].strip()
            # if soft constraint, it is handled differently from hard constraint
            if tokens[1].strip() == 'ends-by':
                # need to retain day time and cost from the line
                # must have task, 'end-by', day, time, cost
                # or task, 'end-by', day, cost
                # or task, 'end-by', time, cost

```

```

        if len(tokens) != 5:
            return None
        # get the rest of the line after 'ends-by'
        soft_costs[key] = int(tokens[len(tokens)-1].strip()) # last
        # pass the day time string to avoid passing param_type
        day_time_str = tokens[2] + ' ' + tokens[3]
        soft_day_time[key] = day_time_str
        cost_functions[key] = self.get_cost_function(tokens[1].strip)
    else:
        # the rest of domain spec, after key, are hard unary domain
        # func spec has day time, we also need duration
        dur = durations[key]
        func_spec = line_token2[len(key):].strip()
        domains[key] = self.apply_hard_constraint(domains[key], dur,
    elif line_token1 == 'constraint': # all binary constraints
        constraints.append(self.get_binary_constraint(line_token2, durat
    else:
        return None

    return CSP_with_Cost(domains, durations, constraints, cost_functions, so

def create_CSP_from_spec(spec: str):
    input_lines = list()
    spec = spec.split('\n')
    # strip comments
    for input_line in spec:
        input_line = input_line.split('#')
        if len(input_line[0]) > 0:
            input_lines.append(input_line[0])
            print(input_line[0])
    # construct initial CSP problem
    csp = CSP_builder()
    csp_problem = csp.get_CSP_with_Cost(input_lines)
    return csp_problem

```

5. Greedy Search Constraint Solver using Domain Splitting and Arc Consistency

Create a GreedySearcher to search over the CSP.

The *cost* function for CSP nodes is used as the heuristic, but is actually a direct estimate of the total path cost function f used in A* Search.

In [312...]

```

from searchGeneric import AStarSearcher
class GreedySearcher(AStarSearcher):
    """ returns a searcher for a problem.
    Paths can be found by repeatedly calling search().
    """
    def add_to_frontier(self, path):
        """ add path to the frontier with the appropriate cost """
        # value = path.cost + self.problem.heuristic(path.end()) -- A* definition
        value = path.end().cost
        self.frontier.add(path, value)

```

Run the GreedySearcher on the CSP derived from the sample input.

Note: The solution cost will always be 0 (which is wrong for the sample input) until you write the cost function in the cell above.

In [313...]:

```
# Sample problem specification

sample_spec = """
# two tasks with two binary constraints and soft deadlines
task, t1 3
task, t2 4
# two binary constraints
constraint, t1 before t2
constraint, t1 same-day t2
# domain constraint
domain, t2 mon
# soft deadlines
domain, t1 ends-by mon 3pm 10
domain, t2 ends-by mon 3pm 10
""""
```

In [314...]:

```
# display details (0 turns off)
Con_solver.max_display_level = 0
Search_with_AC_from_Cost_CSP.max_display_level =0
GreedySearcher.max_display_level = 1

def test_csp_solver(searcher):
    final_path = searcher.search()

    if final_path == None:
        print('No solution')
    else:
        domains = final_path.end().domains
        result_str = ''
        for name, domain in domains.items():
            for n in domain:
                result_str += '\n'+str(name)+': '+Day_Time().week_hour_number_to
print(result_str[1:]+\ncost: '+str(final_path.end().cost))

csp_problem = create_CSP_from_spec(sample_spec)
solver = GreedySearcher(Search_with_AC_from_Cost_CSP(csp_problem))
test_csp_solver(solver)
```

```
task, t1 3
task, t2 4
constraint, t1 before t2
constraint, t1 same-day t2
domain, t2 mon
domain, t1 ends-by mon 3pm 10
domain, t2 ends-by mon 3pm 10
Solution: title of csp (cost: 0)
1 paths have been expanded and 0 paths remain in the frontier
t1: mon 9am
t2: mon 12pm
cost: 0
```

6. Depth-First Search Constraint Solver

The Depth-First Constraint Solver in AI^{Python} by default uses a random ordering of the variables in the CSP.

We need to modify this code to make it compatible with the arc consistency solver.

Run the solver by calling `dfs_solve1` (first solution) or `dfs_solve_all` (all solutions).

In [315...]

```
num_expanded = 0
display = False

def dfs_solver(constraints, domains, context, var_order):
    """ generator for all solutions to csp
        context is an assignment of values to some of the variables
        var_order is a list of the variables in csp that are not in context
    """
    global num_expanded, display
    to_eval = {c for c in constraints if c.can_evaluate(context)}
    if all(c.holds(context) for c in to_eval):
        if var_order == []:
            print("Nodes expanded to reach solution:", num_expanded)
            yield context
        else:
            rem_cons = [c for c in constraints if c not in to_eval]
            var = var_order[0]
            for val in domains[var]:
                if display:
                    print("Setting", var, "to", val)
                num_expanded += 1
                yield from dfs_solver(rem_cons, domains, context|{var:val}, var_order)

def dfs_solve_all(csp, var_order=None):
    """ depth-first CSP solver to return a list of all solutions to csp """
    global num_expanded
    num_expanded = 0
    if var_order == None:    # use an arbitrary variable order
        var_order = list(csp.domains)
    return list(dfs_solver(csp.constraints, csp.domains, {}, var_order))

def dfs_solve1(csp, var_order=None):
    """ depth-first CSP solver """
    global num_expanded
    num_expanded = 0
    if var_order == None:    # use an arbitrary variable order
        var_order = list(csp.domains)
    for sol in dfs_solver(csp.constraints, csp.domains, {}, var_order):
        return sol  # return first one
```

Run the Depth-First Solver on the sample problem.

Note: Again there are no costs calculated.

In [316...]

```
def test_dfs_solver(csp_problem):
    solution = dfs_solve1(csp_problem)
    if solution == None:
        print('No solution')
    else:
        result_str = ''
        for name in solution.keys():
            result_str += '\n'+str(name)+': '+Day_Time().week_hour_number_to_day
        print(result_str[1:])
```

```
# call the Depth-First Search solver
csp_problem = create_CSP_from_spec(sample_spec)
test_dfs_solver(csp_problem) # set display to True to see nodes expanded

task, t1 3
task, t2 4
constraint, t1 before t2
constraint, t1 same-day t2
domain, t2 mon
domain, t1 ends-by mon 3pm 10
domain, t2 ends-by mon 3pm 10
Nodes expanded to reach solution: 5
t1: mon 9am
t2: mon 12pm
```

7. Depth-First Search Constraint Solver using Forward Checking with MRV Heuristic

The Depth-First Constraint Solver in AI`Python` by default uses a random ordering of the variables in the CSP.

We redefine the `dfs_solver` methods to implement the MRV (Minimum Remaining Values) heuristic using forward checking.

Because the AI`Python` code is designed to manipulate domain sets, we also need to redefine `can_evaluate` to handle partial assignments.

```
In [317...]: num_expanded = 0
display = False

def can_evaluate(c, assignment):
    """ assignment is a variable:value dictionary
        returns True if the constraint can be evaluated given assignment
    """
    return assignment != {} and all(v in assignment.keys() and type(assignment[v]) == int for v in c.variables)

def mrv_dfs_solver(constraints, domains, context, var_order):
    """ generator for all solutions to csp.
        context is an assignment of values to some of the variables.
        var_order is a list of the variables in csp that are not in context.
    """
    global num_expanded, display
    if display:
        print("Context", context)
    to_eval = {c for c in constraints if can_evaluate(c, context)}
    if all(c.holds(context) for c in to_eval):
        if var_order == []:
            print("Nodes expanded to reach solution:", num_expanded)
            yield context
        else:
            rem_cons = [c for c in constraints if c not in to_eval] # constraint
            var = var_order[0]
            rem_vars = var_order[1:]
            for val in domains[var]:
                if display:
                    print("Setting", var, "to", val)
                num_expanded += 1
                rem_context = context | {var:val}
                if can_evaluate(rem_cons, rem_context):
                    yield from mrv_dfs_solver(rem_cons, domains, rem_context, rem_vars)
```

```

# apply forward checking on remaining variables
if len(var_order) > 1:
    rem_vars_original = list((v, list(domains[v].copy())) for v
    if display:
        print("Original domains:", rem_vars_original)
    # constraints that can't already be evaluated in rem_cons
    rem_cons_ff = [c for c in constraints if c in rem_cons and not
    for rem_var in rem_vars:
        # constraints that can be evaluated by adding a value of
        any_value = list(domains[rem_var])[0]
        rem_to_eval = {c for c in rem_cons_ff if can_evaluate(c,
        # new domain for rem_var are the values for which all ne
        rem_vals = domains[rem_var].copy()
        for rem_val in domains[rem_var]:
            # no constraint with rem_var in the existing context
            for c in rem_to_eval:
                if not c.holds(rem_context|{rem_var: rem_val}):
                    if rem_val in rem_vals:
                        rem_vals.remove(rem_val)
            domains[rem_var] = rem_vals
            # order remaining variables by MRV
            rem_vars.sort(key=lambda v: len(domains[v]))
    if display:
        print("After forward checking:", list((v, domains[v]) for
    if rem_vars == [] or all(len(domains[rem_var]) > 0 for rem_var in
        yield from mrv_dfs_solver(rem_cons, domains, context|{var:v})
    # restore original domains if changed through forward checking
    if len(var_order) > 1:
        if display:
            print("Restoring original domain", rem_vars_original)
            for (v, domain) in rem_vars_original:
                domains[v] = domain
        if display:
            print("Nodes expanded so far:", num_expanded)

def mrv_dfs_solve_all(csp, var_order=None):
    """ depth-first CSP solver to return a list of all solutions to csp """
    global num_expanded
    num_expanded = 0
    if var_order == None:      # order variables by MRV
        var_order = list(csp.domains)
        var_order.sort(key=lambda var: len(csp.domains[var]))
    return list(mrv_dfs_solver(csp.constraints, csp.domains, {}, var_order))

def mrv_dfs_solve1(csp, var_order=None):
    """ depth-first CSP solver """
    global num_expanded
    num_expanded = 0
    if var_order == None:      # order variables by MRV
        var_order = list(csp.domains)
        var_order.sort(key=lambda var: len(csp.domains[var]))
    for sol in mrv_dfs_solver(csp.constraints, csp.domains, {}, var_order):
        return sol  # return first one

```

Run this solver on the sample problem.

Note: Again there are no costs calculated.

```
In [318...]: def test_mrv_dfs_solver(csp_problem):
    solution = mrv_dfs_solve1(csp_problem)
    if solution == None:
        print('No solution')
    else:
        result_str = ''
        for name in solution.keys():
            result_str += '\n'+str(name)+': '+Day_Time().week_hour_number_to_day
    print(result_str[1:])

# call the Depth-First MRV Search solver
csp_problem = create_CSP_from_spec(sample_spec)
test_mrv_dfs_solver(csp_problem) # set display to True to see nodes expanded

task, t1 3
task, t2 4
constraint, t1 before t2
constraint, t1 same-day t2
domain, t2 mon
domain, t1 ends-by mon 3pm 10
domain, t2 ends-by mon 3pm 10
Nodes expanded to reach solution: 5
t2: mon 12pm
t1: mon 9am
```

Assignment

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Question 1 (4 marks)

Consider the search spaces for the fuzzy scheduling CSP solvers – domain splitting with arc consistency and the DFS solver (without forward checking).

- Describe the search spaces in terms of start state, successor functions and goal state(s) (1 mark)
- What is the branching factor and maximum depth to find any solution for the two algorithms (ignoring costs)? (1 mark)
- What is the worst case time and space complexity of the two search algorithms? (1 mark)
- Give one example of a fuzzy scheduling problem that is *easier* for the domain splitting with arc consistency solver than it is for the DFS solver, and explain why (1 mark)

For the second and third part-questions, give the answer in a general form in terms of fuzzy scheduling CSP size parameters.

Answers for Question 1

Write the answers here.

Point 1

- For Domain splitting with arc consistency

Startstate: The full CSPs

Successor functions: Select a variable, split the domain, Make each CSP arc consistent.

Goal states: unary domains which is domain consistent and arc consistent

- for DFS solver:

Startstate: Empty assignment.

Successor functions: Assign a value to an unassigned variable that does not conflict with previously assigned values of other variables

Goal states: All variables are assigned a value and all constraints are satisfied

Point 2

- For Domain splitting with arc consistency

Branching factor: 2

Maximum depth: $n * \log_2 d$

- for DFS solver:

Branching factor: d (Size of domain)

Maximum depth: n (Number of variables)

Point 3

- For Domain splitting with arc consistency

worst case time: $d^3 * n^2$

space complexity:

- for DFS solver:

worst case time: d^n

space complexity: n

Point 4

Consider tasks T_1, T_2, T_3 with $T_1 + 1 < T_2, T_2 + 1 < T_3$

Domain splitting with arc consistency can quickly reduce T_2, T_3 's domain, while DFS should explore more space before detect conflicts.

Question 2 (5 marks)

Define the cost function for a fuzzy scheduling CSP (i.e. a node in the search space for domain splitting and arc consistency) as the total cost of the soft deadline constraints violated for all of the variables, assuming that each variable is assigned one of the best possible values from its domain, where a “best” value for a variable v is one that has the lowest cost to violate the soft deadline constraint (if any) for that variable v .

- Implement the cost function in the indicated cell and place a copy of the code below (3 marks)
- What is its computational complexity (give a general form in terms of fuzzy scheduling CSP size parameters)? (1 mark)
- Show that the cost function f never decreases along a path, and explain why this means the search algorithm is optimal (1 mark)

In [319...]

```
def calculate_cost(self):
    """ calculate total cost of current assignment in domains """
    total_cost = 0
    for var in self.variables:
        if var in self.cost_functions:
            best_cost = float('inf')
            for func in self.cost_functions[var]:
                for domain_value in self.domains[var]:
                    value_cost = func(domain_value, self.soft_day_time[var], sel
                        if value_cost < best_cost:
                            best_cost = value_cost
            total_cost += best_cost
    return total_cost
```

Answers for Question 2

Point 2

Complexity $O(d * n)$

Point 3

Because the cost never decreases along a path, the first goal node found by a best-first or A* search (such as Greedy or AStarSearcher) must be the optimal solution — once we pop the first goal, we know no cheaper one can exist.

Question 3 (4 marks)

Conduct an empirical evaluation of the domain splitting CSP solver using the cost function defined as above compared to using no cost function (i.e. the zero cost function, as originally defined in the above cell). Use the *average number of nodes expanded* as a metric to compare the two algorithms.

- Write a function `generate_problem(n)` that takes an integer `n` and generates a problem specification with `n` tasks and a random set of hard constraints and soft

deadline constraints in the correct format for the constraint solvers (2 marks)

Run the CSP solver (with and without the cost function) over a number of problems of size n for a range of values of n .

- Plot the performance of the two constraint solving algorithms on the above metric against n (1 mark)
- Quantify the performance gain (if any) achieved by the use of this cost function (1 mark)

In [320...]

```
import random
import os
def generate_problem(n, seed=32213):

    rng = random.Random(seed)

    days = ["mon", "tue", "wed", "thu", "fri"]
    times = ["9am", "10am", "11am", "12pm", "1pm", "2pm", "3pm", "4pm"]
    lines = []
    lines.append(f"# {n} tasks with random constraints and soft deadlines")

    # set tasks with random durations
    for i in range(1, n+1):
        dur = rng.randint(1, 3) # duration between 1 and 5 hours
        lines.append(f"task, t{i} {dur}")

    # set binary constraints
    binary_types = ["before", "after", "same-day", "starts-at"]
    lines.append("# binary constraints")
    task_names = [f"t{i}" for i in range(1, n+1)]
    for _ in range(max(1, n)):
        a, b = rng.sample(task_names, 2)
        rel = rng.choice(binary_types)
        lines.append(f"constraint, {a} {rel} {b}")

    # set harddomain constraints
    lines.append("# domain constraints")
    domain_types = [
        lambda t: f"domain, {t} {rng.choice(days)}",
        lambda t: f"domain, {t} {rng.choice(times)}",
        lambda t: f"domain, {t} starts-before {rng.choice(days)} {rng.choice(times)}",
        lambda t: f"domain, {t} starts-after {rng.choice(days)} {rng.choice(times)}",
        lambda t: f"domain, {t} ends-before {rng.choice(days)} {rng.choice(times)}",
        lambda t: f"domain, {t} ends-after {rng.choice(days)} {rng.choice(times)}",
        lambda t: f"domain, {t} starts-in {rng.choice(days)} {rng.choice(times)}",
        lambda t: f"domain, {t} ends-in {rng.choice(days)} {rng.choice(times)}",
        lambda t: f"domain, {t} starts-before {rng.choice(times)}",
        lambda t: f"domain, {t} ends-before {rng.choice(times)}",
        lambda t: f"domain, {t} starts-after {rng.choice(times)}",
        lambda t: f"domain, {t} ends-after {rng.choice(times)}",
    ]
    for t in rng.sample(task_names, max(1, n//4)):
        fn = rng.choice(domain_types)
        lines.append(fn(t))

    # set soft deadlines
    lines.append("# soft deadlines")
```

```
for t in task_names:
    d = rng.choice(days)
    time = rng.choice(times)
    penalty = rng.randint(5, 15)
    lines.append(f"domain, {t} ends-by {d} {time} {penalty}")
lines.append("")

return '\n'.join(lines)
```

```
In [321...]:  
for x in range(2, 20):
    print(f"Testing problem with {x} tasks")
    print("=====")
    print(" ")
    old_stdout = sys.stdout
    sys.stdout = open(os.devnull, 'w')
    spec=generate_problem(x,312)

    csp_problem_q3 = create_CSP_from_spec(spec)

    solver = GreedySearcher(Search_with_AC_from_Cost_CSP(csp_problem_q3))
    sys.stdout = old_stdout
    test_csp_solver(solver)
```

```
Testing problem with 2 tasks
=====
```

```
No (more) solutions. Total of 1 paths expanded.
```

```
No solution
```

```
Testing problem with 3 tasks
=====
```

```
Solution: title of csp --> title of csp (cost: 11)
```

```
12 paths have been expanded and 11 paths remain in the frontier
```

```
t1: mon 9am
```

```
t2: mon 1pm
```

```
t3: tue 9am
```

```
cost: 0
```

```
Testing problem with 4 tasks
=====
```

```
No (more) solutions. Total of 1 paths expanded.
```

```
No solution
```

```
Testing problem with 5 tasks
=====
```

```
No (more) solutions. Total of 1 paths expanded.
```

```
No solution
```

```
Testing problem with 6 tasks
=====
```

```
No (more) solutions. Total of 1 paths expanded.
```

```
No solution
```

```
Testing problem with 7 tasks
=====
```

```
Solution: title of csp --> title of csp (cost: 19)
```

```
20 paths have been expanded and 19 paths remain in the frontier
```

```
t1: tue 9am
```

```
t2: tue 9am
```

```
t3: tue 10am
```

```
t4: mon 12pm
```

```
t5: mon 9am
```

```
t6: mon 9am
```

```
t7: mon 12pm
```

```
cost: 0
```

```
Testing problem with 8 tasks
=====
```

```
Solution: title of csp --> title of csp (cost: 18)
```

```
19 paths have been expanded and 18 paths remain in the frontier
```

```
t1: tue 10am
```

```
t2: fri 9am
```

```
t3: mon 9am
```

```
t4: fri 10am
t5: mon 9am
t6: mon 12pm
t7: fri 10am
t8: tue 10am
cost: 0
Testing problem with 9 tasks
=====

Solution: title of csp --> title of csp (cost: 21)
22 paths have been expanded and 21 paths remain in the frontier
t1: tue 9am
t2: tue 12pm
t3: tue 9am
t4: mon 11am
t5: tue 12pm
t6: mon 9am
t7: mon 9am
t8: mon 9am
t9: mon 1pm
cost: 30
Testing problem with 10 tasks
=====

No (more) solutions. Total of 1 paths expanded.
No solution
Testing problem with 11 tasks
=====

No (more) solutions. Total of 1 paths expanded.
No solution
Testing problem with 12 tasks
=====

Solution: title of csp --> title of csp (cost: 27)
28 paths have been expanded and 27 paths remain in the frontier
t1: mon 9am
t2: tue 12pm
t3: tue 9am
t4: mon 11am
t5: mon 12pm
t6: mon 9am
t7: mon 9am
t8: tue 9am
t9: mon 1pm
t10: mon 11am
t11: mon 9am
t12: fri 9am
cost: 0
Testing problem with 13 tasks
```

```
=====
No (more) solutions. Total of 1 paths expanded.  
No solution
```

```
Testing problem with 14 tasks
```

```
=====
No (more) solutions. Total of 1 paths expanded.  
No solution  
Testing problem with 15 tasks
```

```
=====
No (more) solutions. Total of 1 paths expanded.  
No solution  
Testing problem with 16 tasks
```

```
=====
No (more) solutions. Total of 1 paths expanded.  
No solution  
Testing problem with 17 tasks
```

```
=====
No (more) solutions. Total of 1 paths expanded.  
No solution  
Testing problem with 18 tasks
```

```
=====
Solution: title of csp --> title of csp (cost: 36)  
37 paths have been expanded and 36 paths remain in the frontier
```

```
t1: mon 11am
```

```
t2: mon 9am
```

```
t3: mon 11am
```

```
t4: mon 9am
```

```
t5: fri 3pm
```

```
t6: fri 9am
```

```
t7: fri 11am
```

```
t8: mon 9am
```

```
t9: mon 9am
```

```
t10: mon 2pm
```

```
t11: mon 9am
```

```
t12: mon 9am
```

```
t13: mon 9am
```

```
t14: mon 9am
```

```
t15: fri 9am
```

```
t16: wed 9am
```

```
t17: mon 12pm
```

```
t18: fri 12pm
```

```
cost: 0
```

```
Testing problem with 19 tasks
```

```
=====
No (more) solutions. Total of 1 paths expanded.  
No solution
```

```
In [322...]
# implement nodes as CSP problems with cost functions
class CSP_with_Cost(CSP):
    """ cost_functions maps a CSP var, here a task name, to a list of functions
    """
    def __init__(self, domains, durations, constraints, cost_functions, soft_day_time):
        self.domains = domains
        self.variables = self.domains.keys()
        super().__init__("title of csp", self.variables, constraints)
        self.durations = durations
        self.cost_functions = cost_functions
        self.soft_day_time = soft_day_time
        self.soft_costs = soft_costs
        self.cost = self.calculate_cost()

    # specific to fuzzy scheduling CSP problems
    def calculate_cost(self):
        """ this is really a function f = path cost + heuristic to be used by the solver
        cost = 0

        return cost

    def __repr__(self):
        """ string representation of an arc"""
        return "CSP_with_Cost("+str(list(self.domains.keys()))+':'+str(self.cost)
```

```
In [323...]
for x in range(2, 20):
    print(f"Testing problem with {x} tasks")
    print("=====")
    print(" ")
    old_stdout = sys.stdout
    sys.stdout = open(os.devnull, 'w')
    spec=generate_problem(x,312)

    csp_problem_q3 = create_CSP_from_spec(spec)

    solver = GreedySearcher(Search_with_AC_from_CSP(csp_problem_q3))
    sys.stdout = old_stdout
    test_csp_solver(solver)
```

```
Testing problem with 2 tasks
=====
```

```
No (more) solutions. Total of 1 paths expanded.
```

```
No solution
```

```
Testing problem with 3 tasks
=====
```

```
Solution: title of csp --> title of csp (cost: 11)
```

```
12 paths have been expanded and 11 paths remain in the frontier
```

```
t1: mon 9am
```

```
t2: mon 1pm
```

```
t3: tue 9am
```

```
cost: 0
```

```
Testing problem with 4 tasks
=====
```

```
No (more) solutions. Total of 1 paths expanded.
```

```
No solution
```

```
Testing problem with 5 tasks
=====
```

```
No (more) solutions. Total of 1 paths expanded.
```

```
No solution
```

```
Testing problem with 6 tasks
=====
```

```
No (more) solutions. Total of 1 paths expanded.
```

```
No solution
```

```
Testing problem with 7 tasks
=====
```

```
Solution: title of csp --> title of csp (cost: 19)
```

```
20 paths have been expanded and 19 paths remain in the frontier
```

```
t1: tue 9am
```

```
t2: tue 9am
```

```
t3: tue 10am
```

```
t4: mon 12pm
```

```
t5: mon 9am
```

```
t6: mon 9am
```

```
t7: mon 12pm
```

```
cost: 0
```

```
Testing problem with 8 tasks
=====
```

```
Solution: title of csp --> title of csp (cost: 18)
```

```
19 paths have been expanded and 18 paths remain in the frontier
```

```
t1: tue 10am
```

```
t2: fri 9am
```

```
t3: mon 9am
```

```
t4: fri 10am
t5: mon 9am
t6: mon 12pm
t7: fri 10am
t8: tue 10am
cost: 0
Testing problem with 9 tasks
=====

Solution: title of csp --> title of csp (cost: 21)
22 paths have been expanded and 21 paths remain in the frontier
t1: tue 9am
t2: tue 12pm
t3: tue 9am
t4: mon 11am
t5: tue 12pm
t6: mon 9am
t7: mon 9am
t8: mon 9am
t9: mon 1pm
cost: 0
Testing problem with 10 tasks
=====

No (more) solutions. Total of 1 paths expanded.
No solution
Testing problem with 11 tasks
=====

No (more) solutions. Total of 1 paths expanded.
No solution
Testing problem with 12 tasks
=====

Solution: title of csp --> title of csp (cost: 27)
28 paths have been expanded and 27 paths remain in the frontier
t1: mon 9am
t2: tue 12pm
t3: tue 9am
t4: mon 11am
t5: mon 12pm
t6: mon 9am
t7: mon 9am
t8: tue 9am
t9: mon 1pm
t10: mon 11am
t11: mon 9am
t12: fri 9am
cost: 0
Testing problem with 13 tasks
```


Answers for Question 3

In [324...]

```
results = [
    (3, 12, 12),
    (7, 20, 20),
    (8, 19, 19),
    (9, 22, 22),
    (12, 28, 28),
    (18, 39, 37)
]
```

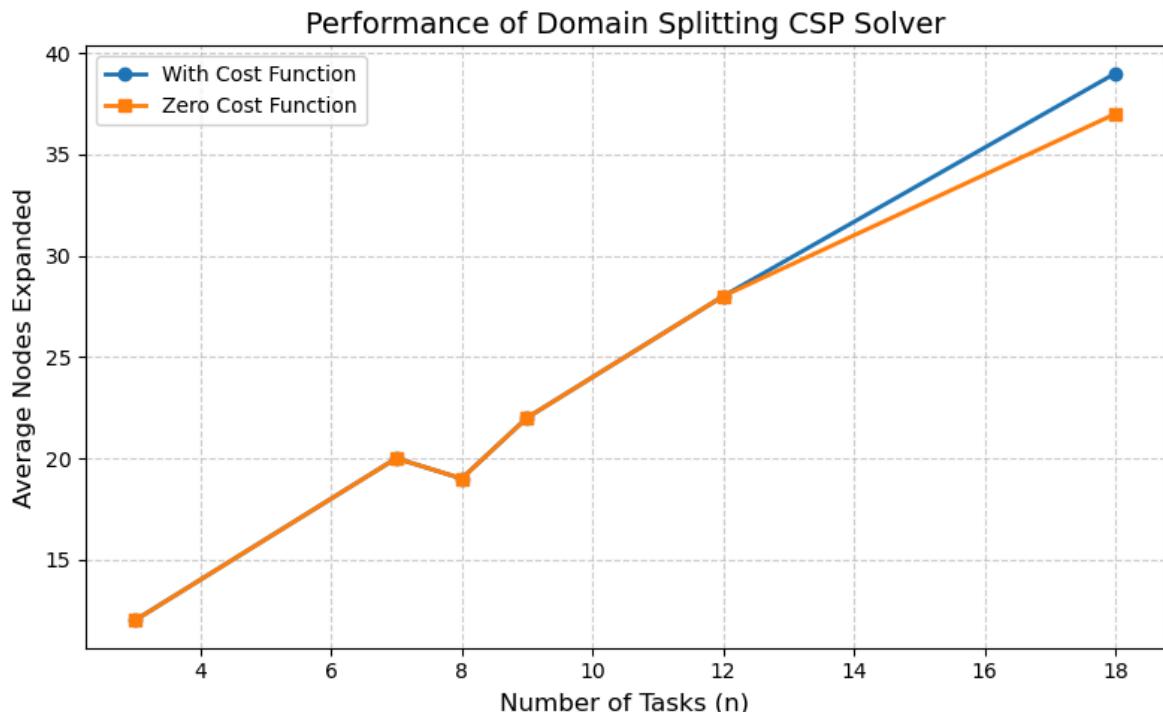
In [325...]

```
import matplotlib.pyplot as plt

# unpack data
n, with_cost, zero_cost = zip(*results)

plt.figure(figsize=(8, 5))
plt.plot(n, with_cost, marker='o', label='With Cost Function', linewidth=2)
plt.plot(n, zero_cost, marker='s', label='Zero Cost Function', linewidth=2)

plt.xlabel('Number of Tasks (n)', fontsize=12)
plt.ylabel('Average Nodes Expanded', fontsize=12)
plt.title('Performance of Domain Splitting CSP Solver', fontsize=14)
plt.legend()
plt.grid(True, linestyle='--', alpha=0.6)
plt.tight_layout()
plt.show()
```



No performance gain found

Question 4 (5 marks)

Compare the Depth-First Search (DFS) solver to the Depth-First Search solver using forward checking with Minimum Remaining Values heuristic (DFS-MRV). For this

question, ignore the costs associated with the CSP problems.

- What is the worst case time and space complexity of each algorithm (give a general form in terms of fuzzy scheduling problem sizes)? (1 mark)
- What are the properties of the search algorithms (completeness, optimality)? (1 mark)
- Give an example of a problem that is *easier* for the DFS-MRV solver than it is for the DFS solver, and explain why (1 mark)
- Empirically compare the quality of the first solution found by DFS and DFS-MRV compared to the optimal solution (1 mark)
- Empirically compare DFS-MRV with DFS in terms of the number of nodes expanded (1 mark)

For the empirical evaluations, run the two algorithms on a variety of problems of size n for varying n . Note that the domain splitting CSP solver with costs should always find an optimal solution.

Point 1

- For DFS

worst case time: $O(d^n)$

space complexity: n

- for DFS-MRV

worst case time: $O(d^n)$

space complexity: $n * d$

Point 2

If the search space is finite and has no circle, DFS is complete. Otherwise, DFS is **not** complete.

DFS is not optimal. It can't guarantee finding the best solution.

Point 3

Consider scheduling as follow:

In [326...]

```
spec="""
task, t1 2
task, t2 2
task, t3 2
constraint, t1 before t2
constraint, t2 before t3
constraint, t1 same-day t2
constraint, t2 same-day t3
domain, t1 mon
```

```
domain, t2 mon
domain, t3 mon
domain, t1 ends-by mon 10am 5
domain, t2 ends-by mon 1pm 5
domain, t3 ends-by mon 5pm 5
....
```

Compare DFS with DFS-MRV

In [327...]

```
old_stdout = sys.stdout
sys.stdout = open(os.devnull, 'w')
csp_problem_q3 = create_CSP_from_spec(spec)
sys.stdout = old_stdout
print("---- DFS Solver ----")
test_dfs_solver(csp_problem_q3)
print("---- MRV-DFS Solver ----")
test_mrv_dfs_solver(csp_problem_q3)
```

```
---- DFS Solver ----
Nodes expanded to reach solution: 9
t1: mon 9am
t2: mon 11am
t3: mon 1pm
---- MRV-DFS Solver ----
Nodes expanded to reach solution: 3
t1: mon 9am
t2: mon 11am
t3: mon 1pm
```

We can find that MRV-DFS Solver only need 3 nodes to reach answer. Because DFS-MRV can detect conflicts earlier and focus on feasible solutions more quickly.

Answer for point 4 & 5

DFS

In [328...]

```
for x in range(2, 8):
    print(f"Testing problem with {x} tasks")
    print("=====")
    print(" ")
    old_stdout = sys.stdout
    sys.stdout = open(os.devnull, 'w')
    spec=generate_problem(x,137)

    csp_problem_q3 = create_CSP_from_spec(spec)

    solver = create_CSP_from_spec(spec)
    sys.stdout = old_stdout
    test_dfs_solver(solver)
```

```

Testing problem with 2 tasks
=====
No solution
Testing problem with 3 tasks
=====

No solution
Testing problem with 4 tasks
=====

No solution
Testing problem with 5 tasks
=====

Nodes expanded to reach solution: 166834
t1: tue 9am
t2: tue 9am
t3: tue 2pm
t4: tue 12pm
t5: tue 10am
Testing problem with 6 tasks
=====

Nodes expanded to reach solution: 309
t1: mon 9am
t2: mon 9am
t3: mon 1pm
t4: mon 11am
t5: mon 10am
t6: mon 10am
Testing problem with 7 tasks
=====

Nodes expanded to reach solution: 8943
t1: fri 9am
t2: fri 9am
t3: fri 10am
t4: fri 12pm
t5: fri 11am
t6: fri 11am
t7: fri 9am

```

DFS-MRV

```

In [329...]: for x in range(2, 8):
    print(f"Testing problem with {x} tasks")
    print("=====")
    print(" ")
    old_stdout = sys.stdout
    sys.stdout = open(os.devnull, 'w')
    spec=generate_problem(x,137)

    csp_problem_q3 = create_CSP_from_spec(spec)

    solver = create_CSP_from_spec(spec)
    sys.stdout = old_stdout
    test_mrv_dfs_solver(solver)

```

```

Testing problem with 2 tasks
=====
No solution
Testing problem with 3 tasks
=====

No solution
Testing problem with 4 tasks
=====

No solution
Testing problem with 5 tasks
=====

Nodes expanded to reach solution: 5
t4: tue 12pm
t1: tue 9am
t5: tue 10am
t2: tue 9am
t3: tue 2pm
Testing problem with 6 tasks
=====

Nodes expanded to reach solution: 17
t3: mon 1pm
t4: mon 11am
t5: mon 10am
t1: mon 9am
t2: mon 9am
t6: mon 10am
Testing problem with 7 tasks
=====

Nodes expanded to reach solution: 8
t3: fri 10am
t1: fri 9am
t4: fri 12pm
t5: fri 11am
t7: fri 9am
t6: fri 11am
t2: fri 9am

```

- Answer for point 4:

As we can see in problems with seed = 137: For small fuzzy scheduling problems, the first feasible solution found by plain DFS was often identical or very close in cost to the optimal solution produced by DFS-MRV or the domain-splitting solver with costs.

This occurs because small problems have limited search spaces and strong constraints, so DFS naturally encounters near-optimal assignments early in the search.

As the number of tasks increases, DFS should begin to explore many branches, and the benefits of MRV and forward checking will become significant.

- Answer for point 5:

From the result above, we can also find that even if the same solution is generated, the number of nodes that need to be expanded by DFS-MRV is much smaller than the basic DFS.

Question 5 (4 marks)

The DFS solver chooses variables in random order, and systematically explores all values for those variables in no particular order.

Incorporate costs into the DFS constraint solver as heuristics to guide the search. Similar to the cost function for the domain splitting solver, for a given variable v , the cost of assigning the value val to v is the cost of violating the soft deadline constraint (if any) associated with v for the value val . The *minimum cost* for v is the lowest cost from amongst the values in the domain of v . The DFS solver should choose a variable v with lowest minimum cost, and explore its values in order of cost from lowest to highest.

- Implement this behaviour by modifying the code in `dfs_solver` and place a copy of the code below (2 marks)
- Empirically compare the performance of DFS with and without these heuristics (2 marks)

For the empirical evaluations, again run the two algorithms on a variety of problems of size n for varying n .

```
In [330]:  
def value_cost(csp, var, val):  
    total_cost = 0  
    if var in csp.cost_functions:  
        for func in csp.cost_functions[var]:  
            cost = func(val, csp.soft_day_time[var], csp.durations[var], csp.soft)  
            total_cost += cost  
    return total_cost  
  
def dfs_solver_with_cost(csp, constraints, domains, context, var_order):  
    """ generator for all solutions to csp  
        context is an assignment of values to some of the variables  
        var_order is a list of the variables in csp that are not in context  
    """  
  
    global num_expanded, display  
    to_eval = {c for c in constraints if c.can_evaluate(context)}  
    if all(c.holds(context) for c in to_eval):  
        if var_order == []:  
            print("Nodes expanded to reach solution:", num_expanded)  
            yield context  
        else:  
            rem_cons = [c for c in constraints if c not in to_eval]  
  
            best_var = None  
            best_min = float('inf')  
            for v in var_order:  
                Dv = domains[v]  
                if not Dv: continue  
                for val in Dv:  
                    new_context = context.copy()  
                    new_context[v] = val  
                    new_cost = value_cost(csp, v, val)  
                    if new_cost < best_min:  
                        best_min = new_cost  
                        best_var = v  
            if best_var is not None:  
                yield from dfs_solver_with_cost(csp, rem_cons, domains, new_context,  
                                                var_order[:var_order.index(best_var)])  
            else:  
                yield context
```

```

        m = min(value_cost(csp, v, val) for val in Dv)
        if m < best_min:
            best_min = m; best_var = v

    var = best_var if best_var is not None else var_order[0]

    # sort values by cost
    ordered_vals = sorted(domains[var], key=lambda val: value_cost(csp,

for val in ordered_vals:
    if display:
        print("Setting", var, "to", val)
    num_expanded += 1
    yield from dfs_solver_with_cost(csp, rem_cons, domains, context|)

def dfs_solve_all_with_cost(csp, var_order=None):
    """ depth-first CSP solver to return a list of all solutions to csp """
    global num_expanded
    num_expanded = 0
    if var_order == None:    # use an arbitrary variable order
        var_order = list(csp.domains)
    return list(dfs_solver_with_cost(csp, csp.constraints, csp.domains, {}, var_)

def dfs_solve1_with_cost(csp, var_order=None):
    """ depth-first CSP solver """
    global num_expanded
    num_expanded = 0
    if var_order == None:    # use an arbitrary variable order
        var_order = list(csp.domains)
    for sol in dfs_solver_with_cost(csp, csp.constraints, csp.domains, {}, var_o
        return sol # return first one

def test_dfs_solver_with_cost(csp_problem):
    solution = dfs_solve1_with_cost(csp_problem)
    if solution == None:
        print('No solution')
    else:
        result_str = ''
        for name in solution.keys():
            result_str += '\n'+str(name)+': '+Day_Time().week_hour_number_to_day
    print(result_str[1:])

```

In [331...]

```

for x in range(2, 8):
    print(f"Testing problem with {x} tasks")
    print("=====")
    print(" ")
    old_stdout = sys.stdout
    sys.stdout = open(os.devnull, 'w')
    spec=generate_problem(x,137)

    csp_problem_q3 = create_CSP_from_spec(spec)

    solver = create_CSP_from_spec(spec)
    sys.stdout = old_stdout
    test_dfs_solver(solver)

```

```
Testing problem with 2 tasks
=====
No solution
Testing problem with 3 tasks
=====

No solution
Testing problem with 4 tasks
=====

No solution
Testing problem with 5 tasks
=====

Nodes expanded to reach solution: 166834
t1: tue 9am
t2: tue 9am
t3: tue 2pm
t4: tue 12pm
t5: tue 10am
Testing problem with 6 tasks
=====

Nodes expanded to reach solution: 309
t1: mon 9am
t2: mon 9am
t3: mon 1pm
t4: mon 11am
t5: mon 10am
t6: mon 10am
Testing problem with 7 tasks
=====

Nodes expanded to reach solution: 8943
t1: fri 9am
t2: fri 9am
t3: fri 10am
t4: fri 12pm
t5: fri 11am
t6: fri 11am
t7: fri 9am
```

```
In [332]:  
for x in range(2, 8):
    print(f"Testing problem with {x} tasks")
    print("=====")
    print(" ")
    old_stdout = sys.stdout
    sys.stdout = open(os.devnull, 'w')
    spec=generate_problem(x,137)

    csp_problem_q3 = create_CSP_from_spec(spec)

    solver = create_CSP_from_spec(spec)
    sys.stdout = old_stdout
    test_dfs_solver_with_cost(solver)
```

```

Testing problem with 2 tasks
=====
No solution
Testing problem with 3 tasks
=====

No solution
Testing problem with 4 tasks
=====

No solution
Testing problem with 5 tasks
=====

Nodes expanded to reach solution: 166834
t1: tue 9am
t2: tue 9am
t3: tue 2pm
t4: tue 12pm
t5: tue 10am
Testing problem with 6 tasks
=====

Nodes expanded to reach solution: 309
t1: mon 9am
t2: mon 9am
t3: mon 1pm
t4: mon 11am
t5: mon 10am
t6: mon 10am
Testing problem with 7 tasks
=====

Nodes expanded to reach solution: 4246805
t1: fri 9am
t2: fri 9am
t4: fri 12pm
t5: fri 11am
t6: fri 11am
t7: fri 9am
t3: fri 10am

```

Answers for Question 5

Because the heuristic algorithm only determines the order of variable and value selection based on soft constraints (soft cost) without considering hard constraints (such as the order of tasks, structural constraints such as the same day), in some cases it will be "misled" to branches with lower costs but more likely to violate hard constraints, resulting in a large amount of backtracking, an increase in the overall number of expanded nodes, and a decrease in performance.

As we can find in the problem with 7 tasks. The DFS and DFS with heuristic algorithm find a same solution. However, DFS with heuristic algorithm take 4246805 nodes to reach solution while DFS only need 8943 nodes.

Question 6 (3 marks)

The CSP solver with domain splitting splits a CSP variable domain into *exactly two* partitions. Poole & Mackworth claim that in practice, this is as good as splitting into a larger number of partitions. In this question, empirically evaluate this claim for fuzzy scheduling CSPs.

- Write a new `partition_domain` function that partitions a domain into a list of `k` partitions, where `k` is a parameter to the function (1 mark)
- Modify the CSP solver to use the list of `k` partitions and evaluate the performance of the solver using the above metric for a range of values of `k` (2 marks)

In [333...]

```
def partition_domain(domain, k):
    if k <= 1 or len(domain) <= 1:
        return [domain]

    n = len(domain)
    step = n // k
    partitions = []
    start = 0

    for i in range(k - 1):
        end = start + step
        partitions.append(domain[start:end])
        start = end
    partitions.append(domain[start:])

    return [p for p in partitions if p]
```

In [334...]

```
partition_domain([1,2,3,4,5,6,7,8,9], 3)
```

Out[334...]

```
[[1, 2, 3], [4, 5, 6], [7, 8, 9]]
```

In [335...]

```
sample_spec = generate_problem(7,137)
csp_problem = create_CSP_from_spec(sample_spec)

for k in [2,3,4,5]:
    print(f"---- Domain Splitting with k={k} ----")
    print(" ")
    solver = GreedySearcher(Search_with_AC_from_Cost_CSP(csp_problem, k=k))
    test_csp_solver(solver)
    print(" ")
```

```
task, t1 1
task, t2 1
task, t3 2
task, t4 2
task, t5 1
task, t6 1
task, t7 2
constraint, t3 starts-at t1
constraint, t7 same-day t5
constraint, t4 starts-at t5
constraint, t2 same-day t4
constraint, t1 before t5
constraint, t6 after t7
constraint, t4 after t3
domain, t3 starts-after thu 3pm
domain, t1 ends-by wed 2pm 5
domain, t2 ends-by thu 2pm 6
domain, t3 ends-by wed 10am 8
domain, t4 ends-by mon 2pm 13
domain, t5 ends-by fri 2pm 5
domain, t6 ends-by tue 10am 11
domain, t7 ends-by fri 9am 8
---- Domain Splitting with k=2 ----
```

Solution: title of csp --> title of csp (cost: 6)

7 paths have been expanded and 6 paths remain in the frontier

```
t1: fri 9am
t2: fri 9am
t3: fri 10am
t4: fri 12pm
t5: fri 11am
t6: fri 11am
t7: fri 9am
cost: 0
```

---- Domain Splitting with k=3 ----

Solution: title of csp --> title of csp (cost: 5)

6 paths have been expanded and 9 paths remain in the frontier

```
t1: fri 9am
t2: fri 9am
t3: fri 10am
t4: fri 12pm
t5: fri 11am
t6: fri 11am
t7: fri 9am
cost: 0
```

---- Domain Splitting with k=4 ----

Solution: title of csp --> title of csp --> title of csp --> title of csp --> title of csp (cost: 4)

5 paths have been expanded and 10 paths remain in the frontier

```
t1: fri 9am
t2: fri 9am
t3: fri 10am
t4: fri 12pm
t5: fri 11am
```

```
t6: fri 11am
t7: fri 9am
cost: 0

----- Domain Splitting with k=5 -----

Solution: title of csp --> title of csp --> title of csp --> title of csp --> title of csp (cost: 4)
5 paths have been expanded and 12 paths remain in the frontier
t1: fri 9am
t2: fri 9am
t3: fri 10am
t4: fri 12pm
t5: fri 11am
t6: fri 11am
t7: fri 9am
cost: 0
```

```
In [336...]: import pandas as pd

results = [
    (2, 7, 6),
    (3, 6, 9),
    (4, 5, 10),
    (5, 5, 12)
]

df = pd.DataFrame(results, columns=["k (Partitions)", "Paths Expanded", "Paths in Frontier"])
print(df.to_string(index=False))
```

k (Partitions)	Paths Expanded	Paths in Frontier
2	7	6
3	6	9
4	5	10
5	5	12