

# 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 AIPython (as done below) so the code can be run on either CSE machines or a marker's own machine.
- Do not submit any AIPython code. Hence do not change any AIPython 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 AIPython

You will need AIPython 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 AIPython and run your code (you will not submit any AI Python code).

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

```
In [1]: import sys
        sys.path.append('aipython') # change to your directory
        sys.path # check that aipython is now on the path
```

```
Out[1]: ['/Library/Frameworks/Python.framework/Versions/3.13/lib/python3.13.zip',
        '/Library/Frameworks/Python.framework/Versions/3.13/lib/python3.13',
        '/Library/Frameworks/Python.framework/Versions/3.13/lib/python3.13/lib-dynload',
        '',
        '/Users/devansh/Library/Python/3.13/lib/python/site-packages',
        '/Library/Frameworks/Python.framework/Versions/3.13/lib/python3.13/site-packages',
        '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 [2]: # -*- 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' into a set
        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].strip())
            type2, v2 = self.string_to_week_hour_number(str1.split('-')[1].strip())
            if type1 != type2: return None # error, types in range spec are different
            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 mismatch
            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_hour_number))

# 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 [3]: 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
        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 th
    cost = 0
    # TODO: write cost function
    for var in self.variables:
        if var not in self.domains:
            continue
        if not self.domains[var]:
            continue

        date_str = self.soft_day_time.get(var, "")
        cost_unit = int(self.soft_costs.get(var, 0))
        durat = self.durations.get(var, 0)

        domain = self.domains[var]
        val = next(iter(domain))

        try:
            func = self.cost_functions[var][0]
            if func.__name__ == 'no_cost':
                cost = func(val, 0)
            else:
                temp_cost = func(val, date_str, durat, cost_unit)
                cost += temp_cost
        except Exception:
            continue

    return 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 [4]: 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):

```



```

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.
    """
    neighs = []
    var = select(x for x in node.domains if len(node.domains[x]) > 1) # chos
    if var:
        dom1, dom2 = partition_domain(node.domains[var])
        self.display(2, "Splitting", var, "into", dom1, "and", dom2)
        to_do = self.cons.new_to_do(var, None)
        for dom in [dom1, dom2]:
            newdoms = node.domains | {var: dom} # overwrite domain of var wi
            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_
                neighs.append(Arc(node, csp_node))
            else:
                self.display(2, "...", var, "in", dom, "has no solution")
    return neighs

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 [5]:

```

# 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') # sho

    # 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
    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_ke
    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 par
        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.sam
    return Task_Constraint((tokens[0].strip(), tokens[2].strip()), spec, fun

def get_CSP_with_Cost(self, input_lines):
    # Note: It would be more elegant to make task a class but AIPython is no

```

```

# CSP_with_Cost inherits from CSP, which takes domains and constraints f
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_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 constr
        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 [6]: 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* definitio
        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 [7]: # 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 [8]: # display details (0 turns off)
Con_solver.max_display_level = 0
Search_with_AC_from_Cost_CSP.max_display_level = 2
GreedySearcher.max_display_level = 0

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:]+\nncost: '+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
t1: mon 9am
t2: mon 12pm
cost: 10
```

## 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 [9]: 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_)

def dfs_solver_cost(constraints, domains, context, var_order, csp):
    global num_expanded, display

    to_eva = set()
    for c in constraints:
        if c.can_evaluate(context):
            to_eva.add(c)
    if all(c.holds(context) for c in to_eva):
        if not var_order:
            print("nodes expanded to reach solution:", num_expanded)
            yield context
    else:
        remaining_cons = []
        for c in constraints:
            if c not in to_eva:
                remaining_cons.append(c)

        var_costs = {}
        for v in var_order:
            best = float("inf")
            for val in domains[v]:
                temp_dom = domains.copy()
                temp_dom[v] = {val}
                csp.domains = temp_dom
                c = csp.calculate_cost()
                if c < best:
                    best = c
            var_costs[v] = best

        var = min(var_costs, key=var_costs.get)

        value_costs = []
        for val in domains[var]:
            temp_dom = domains.copy()
            temp_dom[var] = {val}
            csp.domains = temp_dom
            value_costs.append((val, csp.calculate_cost()))

        value_costs.sort(key=lambda x: x[1])

        for val, _ in value_costs:
            if display:
                print(f"Assigning {var} = {val}")
            num_expanded += 1
            yield from dfs_solver_cost(
                remaining_cons,
                domains,
                context | {var: val},
                [x for x in var_order if x != var],
                csp

```

```

    )

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))
    # return list(dfs_solver_cost(csp.constraints, csp.domains, {}, var_order, c

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

def compareDFS(csp, var_order=None):
    import time

    print("normal DFS below")
    start = time.time()
    sol_normal_dfs = list(dfs_solver(csp.constraints, csp.domains, {}, list(csp.d
    end = time.time()
    print("time:", end - start, "seconds")
    print("solutions found:", len(sol_normal_dfs))

    print("\ncost-guided DFS below")
    start = time.time()
    sol_cost = list(dfs_solver_cost(csp.constraints, csp.domains, {}, list(csp.d
    end = time.time()
    print("time:", end - start, "seconds")
    print("solutions found:", len(sol_cost))

    if sol_cost:
        print("\ncost-guided solution:", csp.calculate_cost())

```

Run the Depth-First Solver on the sample problem.

**Note: Again there are no costs calculated.**

```

In [10]: 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
    # compareDFS(csp_problem)

```



```

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 AIPython 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 AIPython code is designed to manipulate domain sets, we also need to redefine `can_evaluate` to handle partial assignments.

```

In [11]: 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]

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}
                # 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 c in rem_cons_ff]
        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, any_value)}
            # new domain for rem_var are the values for which all new constraints hold
            rem_vals = domains[rem_var].copy()
            for rem_val in rem_vals:
                # no constraint with rem_var in the existing context holds
                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 v in rem_vars))
        if rem_vars == [] or all(len(domains[rem_var]) > 0 for rem_var in rem_vars):
            yield from mrv_dfs_solver(rem_cons, domains, context|{var: val for var, val in rem_vars.items()})
        # 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.items():
                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 [12]: 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

**Name:**

**zID:**

### 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

Fuzzy CSP Solvers

1. The start state is a CSP with total of  $n$  variables which do not hold assignment. Each has its initial domain  $d$  which is its max domain size. The successor function chooses a variable  $x$  whose domain size is greater than 1, splits them into two, and the initial domain is halved. The function is also run on child domains recursively. The goal

state is where each variable has domain size of 1 and all hard constraints are satisfied.

2. The branching factor is 2 and maximum depth is the equal to  $\log d$ .
3. The worst case time scenario is  $O(Ad^n)$  where  $A = O(cd^2)$ , where  $c$  is the number of constraints given. The worst space scenario is  $O(n*d)$  as we need to maintain domain for all the variables.

DFS without forward checking

1. The start state is empty with each variable having the size upto domain size  $d$ . The successor function takes a variable  $x$  and assigns a random value from its domain. This continues until all the assignments are fulfilled. If a hard constraint violates, backtrack it. The goal state is a complete assignment of all variables.
2. The branching factor is upto the domain size  $d$ . Maximum depth is equal to total number of variables  $n$ .
3. The worst case time scenario is  $O(d^n)$  where  $d$  is the maximum number of domains and  $n$  is the number of variables to assign. Worst case space scenario is  $O(n)$  since we need  $n$  variables to assign.

Why Domain splitting is easier for fuzzy scheduling problem than DFS

4. If we have 4 tasks  $a, b, c, d$  with durations 1, with each having domain of 9 am to 5 pm. Consider constraints  $a$  before  $b$ ,  $c$  before  $d$ , and some arbitrary unary windows for each as well. Arc consistency will figure out a tiny window for feasibility of a solution and the combinations which will work. DFS will use many  $A$  values which are outside the hard constraints before reaching a possible outcome.

## 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 [13]: # Code for Question 2
# Place a copy of your code here and run it in the relevant cell

def calculate_cost(self):
```

```

""" this is really a function f = path cost + heuristic to be used by th
cost = 0
# TODO: write cost function
for var in self.variables:
    if var not in self.domains:
        continue
    if not self.domains[var]:
        continue

    date_str = self.soft_day_time.get(var, "")
    cost_unit = int(self.soft_costs.get(var, 0))
    durat = self.durations.get(var, 0)

    domain = self.domains[var]
    val = next(iter(domain))

    try:
        func = self.cost_functions[var][0]
        if func.__name__ == 'no_cost':
            cost = func(val, 0)
        else:
            temp_cost = func(val, date_str, durat, cost_unit)
            cost += temp_cost
    except Exception:
        continue

return cost

```

## Answers for Question 2

To calculate computational complexity, for each variable  $n$ , we need all domain values  $d$ . Therefore the complexity is  $O(n*d)$

The CSP algorithm with arc complexity is based on domain splitting. Therefore, minimum cost per variable can only stay the same or increase. It can never decrease.

## 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 [14]: *# Code for Question 3*  
*# Place your code here*

```
import random
import time
import matplotlib.pyplot as plt
import numpy as np

def generate_problem(n):
    random.seed(n)

    lines = []
    days = ['mon', 'tue', 'wed', 'thu', 'fri']

    # tasks
    for i in range(1, n + 1):
        duration = random.randint(1, 4)
        lines.append(f"task, t{i} {duration}")

    # before const
    for _ in range(n // 2):
        a, b = random.sample(range(1, n + 1), 2)
        if a != b:
            lines.append(f"constraint, t{a} before t{b}")

    # same-day const
    for _ in range(n // 3):
        a, b = random.sample(range(1, n + 1), 2)
        if a != b:
            lines.append(f"constraint, t{a} same-day t{b}")

    # domains
    for i in range(1, n + 1):
        day = random.choice(days)
        lines.append(f"domain, t{i} {day}")

    # soft deadlines
    for i in random.sample(range(1, n + 1), n // 3):
        lines.append(f"domain, t{i} ends-by fri 5pm 10")

    print("printing lines here\n", lines)
    return "\n".join(lines)

def run_experiment(ns):

    cost_time = []
    no_cost_time = []

    for n in ns:
        print(f"Running for n = {n} ...")
        problem_str = generate_problem(n)

        # cost function
        start = time.time()
        solver_cost = Con_solver(problem_str)
        solver_cost.use_cost_function = True
        end = time.time()
        cost_time.append(end - start)

        # no cost function
        start = time.time()
```

```

        solver_no_cost = Con_solver(problem_str)
        solver_no_cost.use_cost_function = False
        end = time.time()
        no_cost_time.append(end - start)

    return cost_time, no_cost_time

n = [5, 10, 15, 20, 25]
times_with_cost, times_without_cost = run_experiment(n)

plt.figure(figsize=(7, 5))
plt.plot(n, times_with_cost, 'o-', label='Used Cost Function')
plt.plot(n, times_without_cost, 's--', label='Did not use Cost Function')
plt.xlabel("n")
plt.ylabel("time")
plt.title("CSP Performance Comparison")
plt.legend()
plt.grid(True)
plt.show()

# need to fix this
# times_with_cost = np.array(times_with_cost)
# times_without_cost = np.array(times_without_cost)
# percent_gain = ((times_without_cost - times_with_cost) / times_without_cost) *
# avg_gain = np.mean(percent_gain)
# print(f"Average performance gain from cost function: {avg_gain:.2f}%")

```

Running for n = 5 ...

printing lines here

```
['task, t1 3', 'task, t2 3', 'task, t3 1', 'task, t4 4', 'task, t5 2', 'constraint, t1 before t2', 'constraint, t1 before t3', 'constraint, t4 same-day t2', 'domain, t1 thu', 'domain, t2 fri', 'domain, t3 mon', 'domain, t4 fri', 'domain, t5 tue', 'domain, t1 ends-by fri 5pm 10']
```

Running for n = 10 ...

printing lines here

```
['task, t1 1', 'task, t2 4', 'task, t3 4', 'task, t4 1', 'task, t5 2', 'task, t6 4', 'task, t7 4', 'task, t8 3', 'task, t9 2', 'task, t10 1', 'constraint, t9 before t8', 'constraint, t6 before t2', 'constraint, t4 before t6', 'constraint, t1 before t7', 'constraint, t3 before t6', 'constraint, t7 same-day t10', 'constraint, t5 same-day t10', 'constraint, t8 same-day t3', 'domain, t1 wed', 'domain, t2 wed', 'domain, t3 tue', 'domain, t4 thu', 'domain, t5 tue', 'domain, t6 thu', 'domain, t7 fri', 'domain, t8 thu', 'domain, t9 mon', 'domain, t10 fri', 'domain, t1 ends-by fri 5pm 10', 'domain, t4 ends-by fri 5pm 10', 'domain, t3 ends-by fri 5pm 10']
```

Running for n = 15 ...

printing lines here

```
['task, t1 2', 'task, t2 1', 'task, t3 1', 'task, t4 2', 'task, t5 2', 'task, t6 1', 'task, t7 1', 'task, t8 2', 'task, t9 3', 'task, t10 2', 'task, t11 1', 'task, t12 3', 'task, t13 4', 'task, t14 3', 'task, t15 3', 'constraint, t7 before t5', 'constraint, t6 before t4', 'constraint, t15 before t14', 'constraint, t4 before t14', 'constraint, t6 before t13', 'constraint, t6 before t4', 'constraint, t5 before t12', 'constraint, t9 same-day t7', 'constraint, t4 same-day t10', 'constraint, t8 same-day t14', 'constraint, t7 same-day t8', 'constraint, t2 same-day t8', 'domain, t1 fri', 'domain, t2 wed', 'domain, t3 thu', 'domain, t4 fri', 'domain, t5 wed', 'domain, t6 thu', 'domain, t7 thu', 'domain, t8 mon', 'domain, t9 thu', 'domain, t10 mon', 'domain, t11 tue', 'domain, t12 tue', 'domain, t13 fri', 'domain, t14 tue', 'domain, t15 fri', 'domain, t13 ends-by fri 5pm 10', 'domain, t12 ends-by fri 5pm 10', 'domain, t14 ends-by fri 5pm 10', 'domain, t1 ends-by fri 5pm 10', 'domain, t5 ends-by fri 5pm 10']
```

Running for n = 20 ...

printing lines here

```
['task, t1 2', 'task, t2 3', 'task, t3 1', 'task, t4 3', 'task, t5 2', 'task, t6 1', 'task, t7 4', 'task, t8 4', 'task, t9 1', 'task, t10 1', 'task, t11 2', 'task, t12 3', 'task, t13 4', 'task, t14 4', 'task, t15 4', 'task, t16 2', 'task, t17 2', 'task, t18 3', 'task, t19 3', 'task, t20 3', 'constraint, t14 before t3', 'constraint, t17 before t16', 'constraint, t13 before t3', 'constraint, t7 before t19', 'constraint, t8 before t2', 'constraint, t7 before t4', 'constraint, t3 before t7', 'constraint, t9 before t10', 'constraint, t10 before t9', 'constraint, t6 before t4', 'constraint, t1 same-day t9', 'constraint, t8 same-day t20', 'constraint, t19 same-day t8', 'constraint, t2 same-day t1', 'constraint, t20 same-day t10', 'constraint, t9 same-day t5', 'domain, t1 wed', 'domain, t2 fri', 'domain, t3 thu', 'domain, t4 tue', 'domain, t5 wed', 'domain, t6 fri', 'domain, t7 thu', 'domain, t8 tue', 'domain, t9 tue', 'domain, t10 thu', 'domain, t11 mon', 'domain, t12 tue', 'domain, t13 fri', 'domain, t14 thu', 'domain, t15 wed', 'domain, t16 tue', 'domain, t17 mon', 'domain, t18 fri', 'domain, t19 mon', 'domain, t20 fri', 'domain, t7 ends-by fri 5pm 10', 'domain, t14 ends-by fri 5pm 10', 'domain, t6 ends-by fri 5pm 10', 'domain, t18 ends-by fri 5pm 10', 'domain, t3 ends-by fri 5pm 10', 'domain, t2 ends-by fri 5pm 10']
```

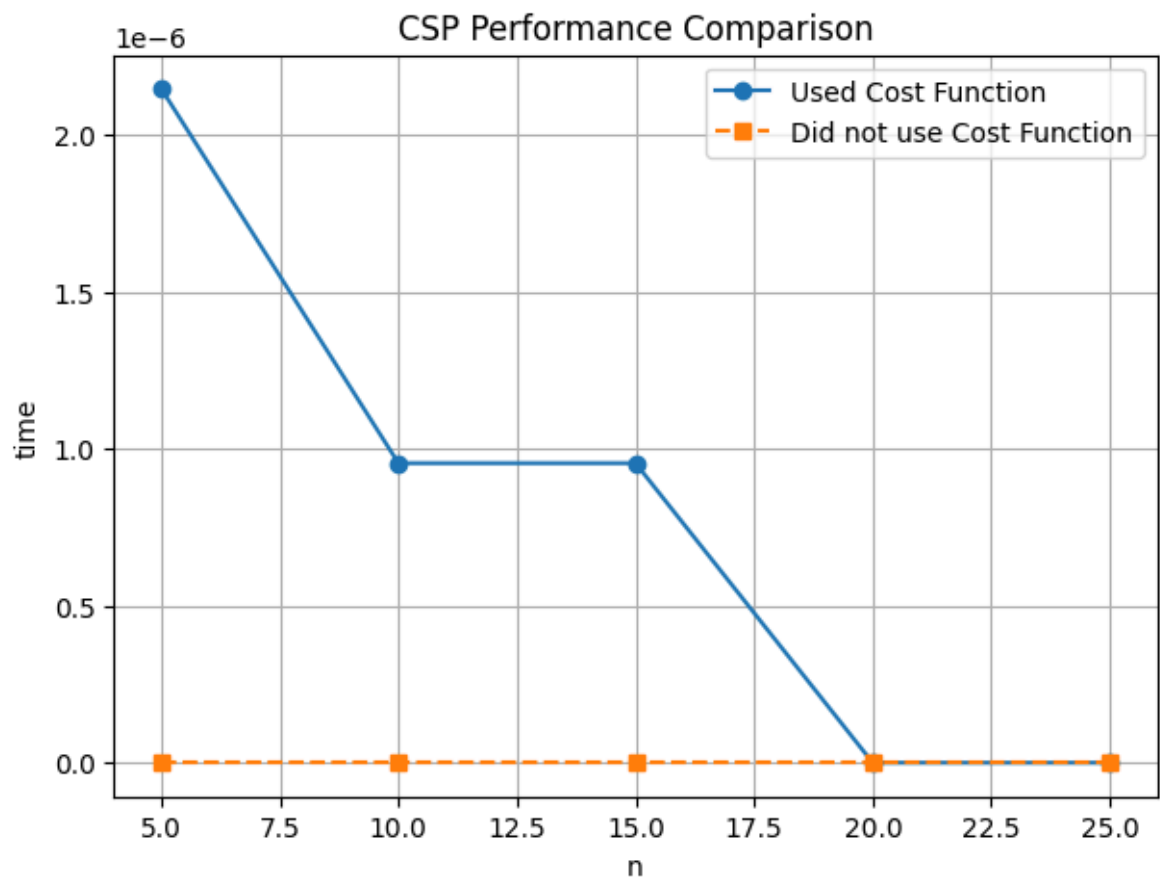
Running for n = 25 ...

printing lines here

```
['task, t1 4', 'task, t2 1', 'task, t3 2', 'task, t4 3', 'task, t5 4', 'task, t6 1', 'task, t7 3', 'task, t8 1', 'task, t9 3', 'task, t10 4', 'task, t11 1', 'task, t12 1', 'task, t13 2', 'task, t14 3', 'task, t15 2', 'task, t16 3', 'task, t17 4', 'task, t18 1', 'task, t19 1', 'task, t20 3', 'task, t21 4', 'task, t22 3', 'task, t23 2', 'task, t24 2', 'task, t25 4', 'constraint, t3 before t13', 'constraint, t19 before t3', 'constraint, t17 before t21', 'constraint, t5 before t24', 'constraint, t2 before t18', 'constraint, t6 before t3', 'constraint, t19 before t
```



8', 'constraint, t25 before t14', 'constraint, t18 before t15', 'constraint, t14 before t16', 'constraint, t20 before t17', 'constraint, t21 before t16', 'constraint, t15 same-day t2', 'constraint, t16 same-day t10', 'constraint, t6 same-day t2', 'constraint, t14 same-day t13', 'constraint, t21 same-day t15', 'constraint, t1 same-day t16', 'constraint, t8 same-day t14', 'constraint, t20 same-day t19', 'domain, t1 wed', 'domain, t2 mon', 'domain, t3 tue', 'domain, t4 mon', 'domain, t5 mon', 'domain, t6 tue', 'domain, t7 tue', 'domain, t8 tue', 'domain, t9 tue', 'domain, t10 tue', 'domain, t11 wed', 'domain, t12 tue', 'domain, t13 tue', 'domain, t14 fri', 'domain, t15 fri', 'domain, t16 fri', 'domain, t17 fri', 'domain, t18 thu', 'domain, t19 wed', 'domain, t20 wed', 'domain, t21 wed', 'domain, t22 thu', 'domain, t23 thu', 'domain, t24 thu', 'domain, t25 thu', 'domain, t22 ends-by fri 5pm 10', 'domain, t14 ends-by fri 5pm 10', 'domain, t15 ends-by fri 5pm 10', 'domain, t13 ends-by fri 5pm 10', 'domain, t12 ends-by fri 5pm 10', 'domain, t17 ends-by fri 5pm 10', 'domain, t4 ends-by fri 5pm 10', 'domain, t9 ends-by fri 5pm 10']



### Answers for Question 3

Quantify Performance Gain

The domain splitting solver performs better than the zero cost version in terms of accuracy, but worse in terms of time, because it takes more time to calculate accuracy. The cost function also allows elimination of high cost pathways at an early stage.

### 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.

```
In [15]: # Code for Question 4
# Place your code here
import time
import matplotlib.pyplot as plt

def compare_dfs_mrv(csp_sizes):
    dfs_nodes = []
    dfs_mrv_nodes = []
    dfs_time = []
    dfs_mrv_time = []

    for n in csp_sizes:
        print(f"\nrunning CSP of size {n}")
        problem_spec = generate_problem(n)
        csp = create_CSP_from_spec(problem_spec)

        # solving for dfs
        global num_expanded
        num_expanded = 0
        start = time.time()
        _ = list(dfs_solver(csp.constraints, csp.domains, {}, list(csp.domains.k
        dfs_time.append(time.time() - start)
        dfs_nodes.append(num_expanded)

        # solving for dfs_mrv
        num_expanded = 0
        start = time.time()
        _ = list(mrv_dfs_solver(csp.constraints, csp.domains, {}, list(csp.domai
        dfs_mrv_time.append(time.time() - start)
        dfs_mrv_nodes.append(num_expanded)

        print(f"DFS nodes: {dfs_nodes[-1]}, time: {dfs_time[-1]:.5f}s")
        print(f"MRV nodes: {dfs_mrv_nodes[-1]}, time: {dfs_mrv_time[-1]:.5f}s")

    # graph results for node expansion
    plt.figure(figsize=(6,4))
    plt.plot(csp_sizes, dfs_nodes, 'o-', label="DFS")
    plt.plot(csp_sizes, dfs_mrv_nodes, 's-', label="DFS-MRV")
    plt.xlabel("n")
    plt.ylabel("expanded nodes")
    plt.title("dfs vs dfs_mrv node expansion")
```

```

plt.legend()
plt.grid(True)
plt.show()

# graph results for execution time
plt.figure(figsize=(6,4))
plt.plot(csp_sizes, dfs_time, 'o-', label="DFS")
plt.plot(csp_sizes, dfs_mrv_time, 's-', label="DFS-MRV")
plt.xlabel("n")
plt.ylabel("time")
plt.title("dfs vs dfs_mrv execution time")
plt.legend()
plt.grid(True)
plt.show()

# percent gain
for n, d_nodes, m_nodes in zip(csp_sizes, dfs_nodes, dfs_mrv_nodes):
    gain = (d_nodes - m_nodes)/d_nodes*100 if d_nodes else 0
    print(f"n={n}: dfs={d_nodes}, dfs_mrv={m_nodes}, gain={gain:.1f}% fewer n

compare_dfs_mrv([4,5,6])

```

running CSP of size 4

printing lines here

```
['task, t1 2', 'task, t2 3', 'task, t3 1', 'task, t4 4', 'constraint, t4 before t1', 'constraint, t1 before t4', 'constraint, t1 same-day t2', 'domain, t1 fri', 'domain, t2 wed', 'domain, t3 mon', 'domain, t4 tue', 'domain, t3 ends-by fri 5pm 10']
```

task, t1 2

task, t2 3

task, t3 1

task, t4 4

constraint, t4 before t1

constraint, t1 before t4

constraint, t1 same-day t2

domain, t1 fri

domain, t2 wed

domain, t3 mon

domain, t4 tue

domain, t3 ends-by fri 5pm 10

DFS nodes: 36, time: 0.00009s

MRV nodes: 6, time: 0.00012s

running CSP of size 5

printing lines here

```
['task, t1 3', 'task, t2 3', 'task, t3 1', 'task, t4 4', 'task, t5 2', 'constraint, t1 before t2', 'constraint, t1 before t3', 'constraint, t4 same-day t2', 'domain, t1 thu', 'domain, t2 fri', 'domain, t3 mon', 'domain, t4 fri', 'domain, t5 tue', 'domain, t1 ends-by fri 5pm 10']
```

task, t1 3

task, t2 3

task, t3 1

task, t4 4

task, t5 2

constraint, t1 before t2

constraint, t1 before t3

constraint, t4 same-day t2

domain, t1 thu

domain, t2 fri

domain, t3 mon

domain, t4 fri

domain, t5 tue

domain, t1 ends-by fri 5pm 10

DFS nodes: 205, time: 0.00026s

MRV nodes: 5, time: 0.00009s

running CSP of size 6

printing lines here

```
['task, t1 1', 'task, t2 4', 'task, t3 3', 'task, t4 1', 'task, t5 1', 'task, t6 2', 'constraint, t6 before t5', 'constraint, t4 before t3', 'constraint, t3 before t1', 'constraint, t3 same-day t4', 'constraint, t2 same-day t4', 'domain, t1 fri', 'domain, t2 fri', 'domain, t3 mon', 'domain, t4 tue', 'domain, t5 fri', 'domain, t6 fri', 'domain, t6 ends-by fri 5pm 10', 'domain, t3 ends-by fri 5pm 10']
```

task, t1 1

task, t2 4

task, t3 3

task, t4 1

task, t5 1

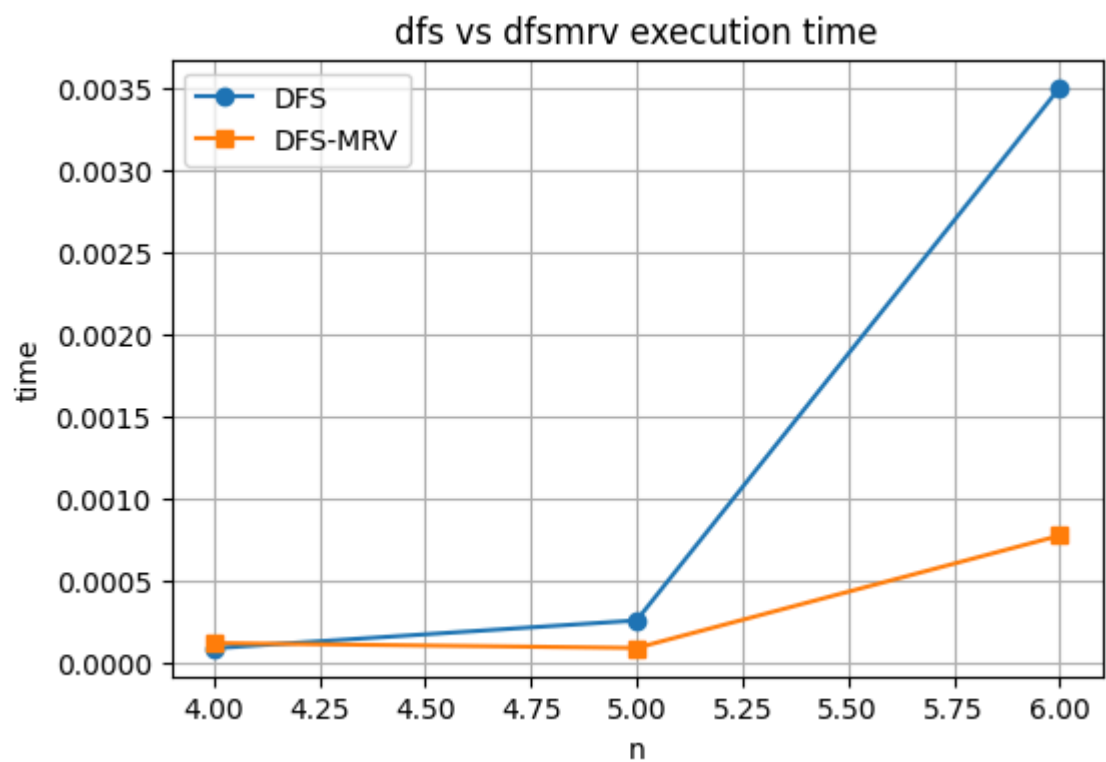
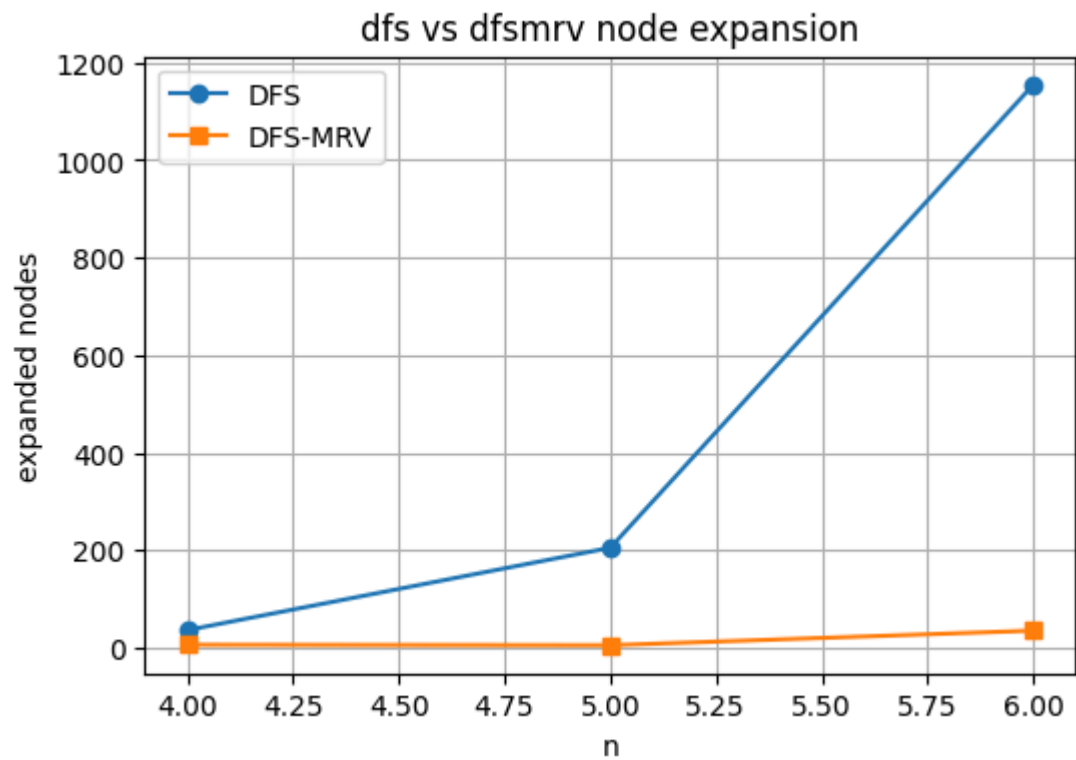
task, t6 2

constraint, t6 before t5

constraint, t4 before t3

constraint, t3 before t1

```
constraint, t3 same-day t4
constraint, t2 same-day t4
domain, t1 fri
domain, t2 fri
domain, t3 mon
domain, t4 tue
domain, t5 fri
domain, t6 fri
domain, t6 ends-by fri 5pm 10
domain, t3 ends-by fri 5pm 10
DFS nodes: 1155, time: 0.00351s
MRV nodes: 35, time: 0.00078s
```



n=4: dfs=36, dfsmr=6, gain=83.3% fewer nodes than regular dfs  
n=5: dfs=205, dfsmr=5, gain=97.6% fewer nodes than regular dfs  
n=6: dfs=1155, dfsmr=35, gain=97.0% fewer nodes than regular dfs

#### Answers for Question 4

DFS without forward checking -  $O(d^n)$  where  $d$  is the maximum domain size and  $n$  is the number of variables. With binary constraints also in the picture, we have to check this against each constraint  $m$ . therefore the complexity is  $O(m \cdot d^n)$ . Space used will be  $O(n)$  since we need  $n$  variables

DFS with forward checking (MRV) - Forward checking uses a heuristic to choose good variables by checking neighbours, so for each of the  $n$  variables, we have  $d$  domains. Moreover, for each assignment, it will check neighbouring values  $x$ , each having  $d$  domains. So time complexity for each assignment is  $O(xd)$ . *Therefore worst case time complexity is  $O(xddn)$ , which is  $O(xdn)$ .* For space, we also need to store a stack for backtracking, so  $O(n + n \cdot d)$  is still  $O(n)$ .

In terms of completeness, both of them are complete. Forward checking is a bit more complex and has heuristic which is able to eliminate too expensive approaches early on. But in terms of finding an optimal solution, both DFS with or without forward checking will not be able to give an optimal approach because they both do not search the whole space, neither follow branching.

An example where the first node A has only 2 domains, and the next nodes B,C have 7 domains, DFS with forward checking while moving from A to B will forward check and eliminate all the nodes except the 2, greatly reducing the unnecessary work for the other nodes, which is done by DFS without forward checking. This way, DFS-MRV will have a more easier approach than regular DFS without forward checking.

#### 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 [16]: # Code for Question 5
# Place a copy of your code here and run it in the relevant cell
def dfs_solver_cost(constraints, domains, context, var_order, csp):
    global num_expanded, display

    to_eva = set()
    for c in constraints:
        if c.can_evaluate(context):
            to_eva.add(c)
    if all(c.holds(context) for c in to_eva):
        if not var_order:
            print("nodes expanded to reach solution:", num_expanded)
            yield context
        else:
            remaining_cons = []
            for c in constraints:
                if c not in to_eva:
                    remaining_cons.append(c)

            var_costs = {}
            for v in var_order:
                best = float("inf")
                for val in domains[v]:
                    temp_dom = domains.copy()
                    temp_dom[v] = {val}
                    csp.domains = temp_dom
                    c = csp.calculate_cost()
                    if c < best:
                        best = c
                var_costs[v] = best

            var = min(var_costs, key=var_costs.get)

            value_costs = []
            for val in domains[var]:
                temp_dom = domains.copy()
                temp_dom[var] = {val}
                csp.domains = temp_dom
                value_costs.append((val, csp.calculate_cost()))

            value_costs.sort(key=lambda x: x[1])

            for val, _ in value_costs:
                if display:
                    print(f"Assigning {var} = {val}")
                num_expanded += 1
                yield from dfs_solver_cost(
                    remaining_cons,
                    domains,
                    context | {var: val},
                    [x for x in var_order if x != var],
                    csp
                )

```

## Answers for Question 5

Write the other answers here.

## 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 [17]: # Code for Question 6
# Place a copy of your code here and run it in the relevant cell
def compareDFS(csp, var_order=None):
    import time

    print("normal DFS below")
    start = time.time()
    sol_normal_dfs = list(dfs_solver(csp.constraints, csp.domains, {}, list(csp.d
    end = time.time()
    print("time:", end - start, "seconds")
    print("solutions found:", len(sol_normal_dfs))

    print("\ncost-guided DFS below")
    start = time.time()
    sol_cost = list(dfs_solver_cost(csp.constraints, csp.domains, {}, list(csp.d
    end = time.time()
    print("time:", end - start, "seconds")
    print("solutions found:", len(sol_cost))

    if sol_cost:
        print("\ncost-guided solution:", csp.calculate_cost())
```

### Answers for Question 6

Write the other answers here.