

# Marmara University

## Faculty of Engineering



## CSE 4082

### Artificial Intelligence

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## Assignment 1

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## Implementation

Our project starts with the main.java file. The main file activates the helper class related to the Knight's Tour and the initial node after receiving the necessary inputs from the user. Then, it runs the TreeSearch.java class to apply the Tree Search algorithm.

The Node.java class represents a square on the board. This class stores the x and y coordinates of the square, as well as the parent node and the visit order (visitedOrder) of the node.

The KnightTour.java class is designed as a helper class that contains all the auxiliary functions to be used during the Tree Search algorithm.

The TreeSearch.java class is where the Tree Search algorithm is implemented. In this class, frontier is defined as a LinkedList. Based on the selected method:

- If the BFS algorithm is chosen, frontier behaves like a queue using offer and poll operations.
- If the algorithm is DFS or one of the heuristic methods, frontier behaves like a stack using push and pop operations.

A loop runs as long as frontier is not empty, during which valid moves for the knight are appropriately added to the frontier. In heuristic methods, a temporary ArrayList is used, and moves are added to the frontier in the appropriate order determined by the heuristic.

Each time a node is removed from the frontier via pop or poll, it is checked whether the node is in the goal state. This check ensures that the visitedOrder value is equal to size x size (the square of the board size). If the values are not equal, the selected node is expanded.

## Problem Definition and Environment

The Knight's Tour Problem (KTP) aims to move a knight across an  $n \times n$  chessboard so that it visits every square exactly once, thereby completing a tour of the entire board.

The movement rules for the knight follow the L-shaped moves used in chess:

- 2 squares horizontally and 1 square vertically, or
- 2 squares vertically and 1 square horizontally.

This problem is classified as a deterministic, single-agent, and fully observable problem.

## Outputs:

We add all relevant outputs to the output file in a text file and image format.

### Breadth-First Search (BFS)

**n = 8**

```
Search Method: Breadth First Search  
Board Size: 8  
Out of Memory.
```

**n = 16**

```
Search Method: Breadth First Search  
Board Size: 16  
Out of Memory.
```

**n = 32**

```
Search Method: Breadth First Search  
Board Size: 32  
Out of Memory.
```

**n = 41**

```
Search Method: Breadth First Search  
Board Size: 41  
Out of Memory.
```

**n = 52**

```
Search Method: Breadth First Search  
Board Size: 52  
Out of Memory.
```

## Depth-First Search (DFS):

**n = 8**

```
Search Method: Depth First Search
Board Size: 8
A solution found.
Time Taken: 1.132 seconds
Nodes expanded: 3242064
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

50	43	30	61	14	63	28	7
31	60	51	42	29	8	13	64
44	49	58	25	62	15	6	27
59	32	45	52	41	26	9	12
48	53	40	57	24	11	16	5
39	56	33	46	35	18	21	10
54	47	2	37	20	23	4	17
1	38	55	34	3	36	19	22

**n = 16**

```
Search Method: Depth First Search
Board Size: 16
Timeout.
Nodes expanded: 1027024630
```

**n = 32**

```
Search Method: Depth First Search
Board Size: 32
Timeout.
Nodes expanded: 359828918
```

**n = 41**

```
Search Method: Depth First Search
Board Size: 41
Timeout.
Nodes expanded: 231197247
```

**n = 52**

```
Search Method: Depth First Search
Board Size: 52
Timeout.
Nodes expanded: 143265975
```

Depth-First Search with Heuristic h1b

**n = 8**

```
Search Method: Depth First Search with Heuristic h1b
Board Size: 8
A solution found.
Time Taken: 0.004 seconds
Nodes expanded: 63
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

46	19	44	5	52	9	58	7
43	4	47	20	57	6	51	10
18	45	42	39	50	53	8	59
3	48	21	56	41	62	11	54
22	17	40	49	38	55	60	63
27	2	25	30	61	36	33	12
16	23	28	37	14	31	64	35
1	26	15	24	29	34	13	32

n = 16

```
Search Method: Depth First Search with Heuristic h1b
Board Size: 16
A solution found.
Time Taken: 0.012 seconds
Nodes expanded: 255
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

98	39	42	9	106	103	44	11	142	117	46	13	128	17	48	15
41	8	97	102	43	10	105	116	45	12	141	118	47	14	121	18
38	95	40	107	104	115	134	113	140	127	132	127	160	119	16	45
7	96	101	114	135	144	139	156	133	188	161	158	131	128	10	122
100	37	108	95	112	153	146	187	202	155	216	189	126	159	50	129
93	6	113	136	165	138	201	154	215	180	235	162	241	130	123	20
36	109	84	111	152	147	186	203	234	217	242	239	236	125	164	51
5	82	87	148	137	200	151	214	191	238	233	246	163	240	21	124
86	35	110	91	150	185	182	231	204	243	218	237	254	245	52	165
75	4	149	88	179	96	199	184	213	232	251	244	247	166	253	22
34	85	76	93	184	193	182	205	238	219	224	227	252	255	248	53
3	74	87	178	89	180	195	188	223	212	229	238	187	226	23	256
66	33	84	77	82	103	206	181	210	197	208	225	228	249	54	171
71	2	73	68	127	78	81	186	207	222	211	188	173	170	57	24
32	65	78	79	30	43	176	202	28	61	174	221	26	59	172	55
1	72	21	64	89	80	29	62	175	208	27	60	169	56	25	58

n = 32

```
Search Method: Depth First Search with Heuristic h1b
Board Size: 32
A solution found.
Time Taken: 0.108 seconds
Nodes expanded: 1023
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

289	75	42	17	202	215	84	19	276	221	86	27	262	217	88	27	266	213	89	25	260	209	92	27	264	205	91	25	268	21	96	31		
91	16	261	288	93	18	275	228	15	29	263	219	17	22	265	204	83	24	269	402	15	26	263	520	35	28	227	814	15	38	181	34		
78	199	36	283	214	227	218	227	274	275	212	281	198	265	176	287	174	343	212	281	176	210	388	285	268	283	284	278	362	855	32	27		
18	264	281	216	287	418	285	274	221	286	282	348	287	294	327	444	342	248	322	148	280	219	327	445	213	246	282	273	346	32	404			
106	71	266	257	268	177	144	278	256	151	276	307	364	387	448	315	444	406	408	371	323	385	363	362	429	271	364	365	746	180	36	183		
286	14	278	219	228	224	263	238	277	334	361	338	353	368	438	418	427	438	517	384	334	384	481	213	263	214	252	278	275	746	487	38		
18	197	210	235	232	251	219	257	252	275	278	380	389	263	385	455	434	360	408	357	346	388	283	210	261	214	279	276	858	188	39			
12	198	182	244	237	262	232	261	266	278	282	344	382	419	381	421	446	362	376	228	386	288	211	262	214	287	418	286	713	274	27	408		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	471	446	368	378	482	355	288	288	218	282	418	286	418	418	418	418	418	418		
188	75	264	257	262	265	224	257	271	281	279	387	476	357	484	355	441	408	524	387	334	387	388	287	288	289	290	291	814	288	161	177		
175	12	265	188	251	181	261	268	337	332	266	384	453	332	463	433	468	516	482	488	278	219	218	218	261	268	417	268	415	268	481	276	431	38
74	197	179	185	248	226	214	273	274	271	190	489	438	265	482	465	511	510	508	387	484	487	288	288	218	283	288	415	410	437	482	191		
12	174	183	246	287	384	287	194	281	274	282	446	472	481	4																			

n = 41

```
Search Method: Depth First Search with Heuristic h1b
Board Size: 41
A solution found.
Time Taken: 12.131 seconds
Nodes expanded: 1061528
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

1	21	31	365	162	388	24	327	174	321	35	178	409	320	31	360	174	320	32	317	444	323	31	326	351	326	36	323	314	322	36	383	314	326	34	362	364	325	32	320	369	322
2	22	32	366	163	389	25	328	175	322	36	179	410	321	32	361	175	321	33	318	445	324	327	37	352	352	37	324	315	323	37	384	315	327	35	363	365	326	33	321	370	323
3	23	33	367	164	390	26	329	176	323	37	180	411	322	33	362	176	322	34	319	446	325	328	38	353	353	38	325	316	324	38	385	316	328	36	364	366	327	34	322	371	324
4	24	34	368	165	391	27	330	177	324	38	181	412	323	34	363	177	323	35	320	447	326	329	39	354	354	39	326	317	325	39	386	317	329	37	365	367	328	35	323	372	325
5	25	35	369	166	392	28	331	178	325	39	182	413	324	35	364	178	324	36	321	448	327	330	40	355	355	40	327	318	326	40	387	318	330	38	366	368	329	36	324	373	326
6	26	36	370	167	393	29	332	179	326	40	183	414	325	36	365	179	325	37	322	449	328	331	41	356	356	41	328	319	327	41	388	319	331	39	367	369	330	37	325	374	327
7	27	37	371	168	394	30	333	180	327	41	184	415	326	37	366	180	326	38	323	450	329	332	42	357	357	42	329	320	328	42	389	320	332	40	368	370	331	38	326	375	328
8	28	38	372	169	395	31	334	181	328	42	185	416	327	38	367	181	327	39	324	451	330	333	43	358	358	43	330	321	329	43	390	321	333	41	369	371	332	39	327	376	329
9	29	39	373	170	396	32	335	182	329	43	186	417	328	39	368	182	328	40	325	452	331	334	44	359	359	44	331	322	330	44	391	322	334	42	370	372	333	40	328	377	330
10	30	40	374	171	397	33	336	183	330	44	187	418	329	40	369	183	329	41	326	453	332	335	45	360	360	45	332	323	331	45	392	323	335	43	371	373	334	41	329	378	331
11	31	41	375	172	398	34	337	184	331	45	188	419	330	41	370	184	330	42	327	454	333	336	46	361	361	46	333	324	332	46	393	324	336	44	372	374	335	42	330	379	332
12	32	42	376	173	399	35	338	185	332	46	189	420	331	42	371	185	331	43	328	455	334	337	47	362	362	47	334	325	333	47	394	325	337	45	373	375	336	43	331	380	333
13	33	43	377	174	400	36	339	186	333	47	190	421	332	43	372	186	332	44	329	456	335	338	48	363	363	48	335	326	334	48	395	326	338	46	374	376	337	44	332	381	334
14	34	44	378	175	401	37	340	187	334	48	191	422	333	44	373	187	333	45	330	457	336	339	49	364	364	49	336	327	335	49	396	327	339	47	375	377	338	45	333	382	335
15	35	45	379	176	402	38	341	188	335	49	192	423	334	45	374	188	334	46	331	458	337	340	50	365	365	50	337	328	336	50	397	328	340	48	376	378	339	46	334	383	336
16	36	46	380	177	403	39	342	189	336	50	193	424	335	46	375	189	335	47	332	459	338	341	51	366	366	51	338	329	337	51	398	329	341	49	377	379	340	47	335	384	337
17	37	47	381	178	404	40	343	190	337	51	194	425	336	47	376	190	336	48	333	460	339	342	52	367	367	52	339	330	338	52	399	330	342	50	378	380	341	48	336	385	338
18	38	48	382	179	405	41	344	191	338	52	195	426	337	48	377	191	337	49	334	461	340	343	53	368	368	53	340	331	339	53	400	331	343	51	379	381	342	49	337	386	339
19	39	49	383	180	406	42	345	192	339	53	196	427	338	49	378	192	338	50	335	462	341	344	54	369	369	54	341	332	340	54	401	332	344	52	380	382	343	50	338	387	340
20	40	50	384	181	407	43	346	193	340	54	197	428	339	50	379	193	339	51	336	463	342	345	55	370	370	55	342	333	341	55	402	333	345	53	381	383	344	51	339	388	341
21	41	51	385	182	408	44	347	194	341	55	198	429	340	51	380	194	340	52	337	464	343	346	56	371	371	56	343	334	342	56	403	334	346	54	382	384	345	52	340	389	342
22	42	52	386	183	409	45	348	195	342	56	199	430	341	52	381	195	341	53	338	465	344	347	57	372	372	57	344	335	343	57	404	335	347	55	383	385	346	53	341	390	343
23	43	53	387	184	410	46	349	196	343	57	200	431	342	53	382	196	342	54	339	466	345	348	58	373	373	58	345	336	344	58	405	336	348	56	384	386	347	54	342	391	344
24	44	54	388	185	411	47	350	197	344	58	201	432	343	54	383	197	343	55	340	467	346	349	59	374	374	59	346	337	345	59	406	337	349	57	385	387	348	55	343	392	345
25	45	55	389	186	412	48	351	198	345	59	202	433	344	55	384	198	344	56	341	468	347	350	60	375	375	60	347	338	346	60	407	338	350	58	386	388	349	56	344	393	346
26	46	56	390	187	413	49	352	199	346	60	203	434	345	56	385	199	345	57	342	469	348	351	61	376	376	61	348	339	347	61	408	339	351	59	387	389	350	57	345	394	347
27	47	57	391	188	414	50	353	200	347	61	204	435	346	57	386	200	346	58	343	470	349	352	62	377	377	62	349	340	348	62	409	340	352	60	388	390	351	58	346	395	348
28	48	58	392	189	415	51	354	201	348	62	205	436	347	58	387	201	347	59	344	471	350	353	63	378	378	63	350	341	349	63	410	341	353	61	389	391	352	59	347	396	349
29	49	59	393	190	416	52	355	202	349	63	206	437	348	59	388	202	348	60	345	472	351	354	64	379	379	64	351	342	350	64	411	342	354	62	390	392	353	60	348	397	350
30	50	60	394	191	417	53	356	203	350	64	207	438	349	60	389	203	349	61	346	473	352	355	65	380	380	65	352	343	351	65	412	343	355	63	391	393	354	61	349	398	351
31	51	61	395	192	418	54	357	204	351	65	208	439	350	61	390	204	350	62	347	474	353	356	66	381	381	66	353	344	352	66	413	344	356	64	392	394	355	62	350	399	352
32	52	62	396	193	419	55	358	205	352	66	209	440	351	62	391	205	351	63	348	475	354	357	67	382	382	67	354	345	353	67	414	345	357	65	393	395	356	63	351	400	353
33	53	63	397	194	420	56	359	206	353	67	210	441	352	63	392	206	352	64	349	476	355	358	68	383	383	68	355	346	354	68	415	346	358	66	394	396	357	64	352	401	354
34	54	64	398	195	421	57	360	207	354	68	211	442	353	64	393	207	353	65	350	477	356	359	69	384	384	69	356	347	355	69	416	347	359	67	395	397	358	65	353	402	355
35	55	65	399	196	422	58	361	208	355	69	212	443	354	65	394	208	354	66	351	478	357	360	70	385	385	70	357	348	356	70	417	348	360	68	396	398	359	66	354	403	356
36	56	66	400	197	423	59	362	209	356	70	213	444	355	66	395	209	355	67	352	479	358	361	71	386	386	71	358	349	357	71	418	349	361	69	397	399	360	67	355	404	357
37	57	67	401	198	424	60	363	210	357	71	214	445	356	67	396	210	356	68	353	480	359	362	72	387	387	72	359	350	358	72	419	350	362	70	398	400	361	68	356	405	358
38	58	68	402	199	425	61	364	211	358	72	215																														

## Depth-First Search with Heuristic h2

**n = 8**

```
Search Method: Depth First Search with Heuristic h2
Board Size: 8
A solution found.
Time Taken: 0.005 seconds
Nodes expanded: 63
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

46	7	58	49	38	9	40	55
59	50	47	8	57	54	37	10
6	45	60	63	48	39	56	41
51	62	33	44	53	64	11	36
20	5	52	61	32	35	42	27
23	2	21	34	43	28	15	12
4	19	24	31	14	17	26	29
1	22	3	18	25	30	13	16

**n = 16**

```
Search Method: Depth First Search with Heuristic h2
Board Size: 16
A solution found.
Time Taken: 0.013 seconds
Nodes expanded: 255
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

68	11	140	177	70	13	96	107	72	15	86	89	74	17	78	81
139	176	69	12	141	106	71	14	97	88	73	16	95	80	75	18
10	67	174	183	178	95	188	105	108	93	98	87	90	77	82	79
175	138	179	142	181	184	223	94	187	104	189	92	99	84	19	76
66	9	182	173	222	189	186	211	254	231	208	103	110	91	100	83
137	62	143	180	185	224	253	232	247	210	251	230	207	182	111	20
8	65	172	221	190	233	212	243	252	255	248	209	249	113	160	101
63	136	61	144	213	244	225	256	237	246	241	250	229	206	21	112
60	7	64	171	220	191	234	245	242	240	236	239	200	161	114	159
53	40	135	58	165	214	219	236	235	238	217	228	205	202	155	22
6	59	54	51	170	133	192	215	218	227	204	201	162	199	158	115
41	52	39	134	57	146	167	196	193	216	163	198	203	154	23	156
38	5	42	55	50	169	132	147	166	187	194	151	164	157	116	127
33	2	31	36	45	56	49	168	195	150	185	124	153	128	119	24
4	37	34	43	30	47	148	131	28	123	152	129	26	121	126	117
1	32	3	46	35	44	29	48	149	130	27	122	125	118	25	120



**n = 32**

```
Search Method: Depth First Search with Heuristic h2
Board Size: 32
A solution found.
Time Taken: 0.133 seconds
Nodes expanded: 1023
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

[illegible]

**n = 41**

```
Search Method: Depth First Search with Heuristic h2
Board Size: 41
A solution found.
Time Taken: 0.452 seconds
Nodes expanded: 1680
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

[illegible]

$n = 52$

```
Search Method: Depth First Search with Heuristic h2
Board Size: 52
A solution found.
Time Taken: 1.653 seconds
Nodes expanded: 2703
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

$n = 273$  (maximum board size that can be toured in 15 minutes)

```
Search Method: Depth First Search with Heuristic h2
Board Size: 273
A solution found.
Time Taken: 897.376 seconds
Nodes expanded: 74528
Solution written to knights_tour_solution.txt
Solution image was saved to knights_tour_solution.png
```

