

Empirical Results

To evaluate the performance of the implemented Insertion Sort algorithm, benchmark experiments were conducted using the provided CLI tool (BenchmarkRunner). The program measured execution time, number of comparisons, shifts, and array accesses for different input sizes and distributions.

All benchmark data were automatically recorded in the file [docs/performance-data.csv](#).

The table below shows a subset of collected results from the benchmark runs:

algorithm	n	distribution	run	time_ns	comparisons	shifts	array_accesses	mem_bytes	binary_insertion
InsertionSort	100	random	1	242042	529	2363	5453	0	true
InsertionSort	100	random	2	160375	535	2393	5519	0	true
InsertionSort	100	random	3	169000	533	2688	6107	0	true
InsertionSort	100	random	4	152417	532	2856	6442	0	true
InsertionSort	100	random	5	152917	541	2660	6059	0	true
InsertionSort	1000	random	1	4087250	8584	247955	506492	0	true
InsertionSort	1000	random	2	338333	8594	250649	511890	0	true
InsertionSort	1000	random	3	1654667	8588	254131	518848	0	true
InsertionSort	1000	random	4	316709	8580	252445	515468	0	true
InsertionSort	1000	random	5	295166	8570	245246	501060	0	true
InsertionSort	10000	random	1	20965125	118992	24817888	49774766	0	true
InsertionSort	10000	random	2	22318292	118942	25250014	50638968	0	true
InsertionSort	10000	random	3	24841709	118996	25094196	50327386	0	true
InsertionSort	10000	random	4	21947584	119029	25003060	50145147	0	true
InsertionSort	10000	random	5	24478334	118980	25066884	50272746	0	true
InsertionSort	100	sorted	1	1709	480	0	678	0	true
InsertionSort	100	sorted	2	1709	480	0	678	0	true
InsertionSort	100	sorted	3	875	480	0	678	0	true
InsertionSort	100	sorted	4	750	480	0	678	0	true
InsertionSort	100	sorted	5	1708	480	0	678	0	true
InsertionSort	1000	sorted	1	8625	7987	0	9985	0	true
InsertionSort	1000	sorted	2	8667	7987	0	9985	0	true
InsertionSort	1000	sorted	3	19166	7987	0	9985	0	true
InsertionSort	1000	sorted	4	21750	7987	0	9985	0	true
InsertionSort	1000	sorted	5	48541	7987	0	9985	0	true
InsertionSort	10000	sorted	1	110625	113631	0	133629	0	true
InsertionSort	10000	sorted	2	114833	113631	0	133629	0	true

InsertionSort	10000	sorted	3	114750	113631	0	133629	0	true
InsertionSort	10000	sorted	4	114708	113631	0	133629	0	true
InsertionSort	10000	sorted	5	117542	113631	0	133629	0	true
InsertionSort	100	reversed	1	5375	573	4950	10671	0	true
InsertionSort	100	reversed	2	5542	573	4950	10671	0	true
InsertionSort	100	reversed	3	5458	573	4950	10671	0	true
InsertionSort	100	reversed	4	5167	573	4950	10671	0	true
InsertionSort	100	reversed	5	5417	573	4950	10671	0	true
InsertionSort	1000	reversed	1	416708	8977	499500	1009975	0	true
InsertionSort	1000	reversed	2	459459	8977	499500	1009975	0	true
InsertionSort	1000	reversed	3	466875	8977	499500	1009975	0	true
InsertionSort	1000	reversed	4	483250	8977	499500	1009975	0	true
InsertionSort	1000	reversed	5	502125	8977	499500	1009975	0	true
InsertionSort	10000	reversed	1	40019583	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	2	39220625	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	3	38754167	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	4	38178875	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	5	38749250	123617	49995000	100133615	0	true
InsertionSort	100	nearly	1	5083	495	69	831	0	true
InsertionSort	100	nearly	2	5167	497	117	929	0	true
InsertionSort	100	nearly	3	917	504	135	972	0	true
InsertionSort	100	nearly	4	4125	490	23	734	0	true
InsertionSort	100	nearly	5	3541	481	7	693	0	true
InsertionSort	1000	nearly	1	72209	8525	9452	29427	0	true
InsertionSort	1000	nearly	2	65167	8460	5264	20986	0	true
InsertionSort	1000	nearly	3	70750	8472	4704	19878	0	true
InsertionSort	1000	nearly	4	68750	8445	7386	25215	0	true
InsertionSort	1000	nearly	5	74667	8589	5556	21699	0	true
InsertionSort	10000	nearly	1	845209	119170	658078	1455324	0	true
InsertionSort	10000	nearly	2	879417	119289	695338	1529963	0	true
InsertionSort	10000	nearly	3	925291	118647	741100	1620845	0	true
InsertionSort	10000	nearly	4	744417	119367	599688	1338741	0	true
InsertionSort	10000	nearly	5	812167	118496	684868	1508230	0	true
InsertionSort	100	random	1	200000	529	2363	5453	0	true
InsertionSort	100	random	2	149792	535	2393	5519	0	true
InsertionSort	100	random	3	169500	533	2688	6107	0	true
InsertionSort	100	random	4	156958	532	2856	6442	0	true
InsertionSort	100	random	5	142167	541	2660	6059	0	true
InsertionSort	1000	random	1	4039459	8584	247955	506492	0	true
InsertionSort	1000	random	2	335209	8594	250649	511890	0	true

InsertionSort	1000	random	3	1645750	8588	254131	518848	0	true
InsertionSort	1000	random	4	298250	8580	252445	515468	0	true
InsertionSort	1000	random	5	283834	8570	245246	501060	0	true
InsertionSort	10000	random	1	21012417	118992	24817888	49774766	0	true
InsertionSort	10000	random	2	21313125	118942	25250014	50638968	0	true
InsertionSort	10000	random	3	22309500	118996	25094196	50327386	0	true
InsertionSort	10000	random	4	25498250	119029	25003060	50145147	0	true
InsertionSort	10000	random	5	21510334	118980	25066884	50272746	0	true
InsertionSort	100	sorted	1	1750	480	0	678	0	true
InsertionSort	100	sorted	2	708	480	0	678	0	true
InsertionSort	100	sorted	3	959	480	0	678	0	true
InsertionSort	100	sorted	4	833	480	0	678	0	true
InsertionSort	100	sorted	5	1542	480	0	678	0	true
InsertionSort	1000	sorted	1	45334	7987	0	9985	0	true
InsertionSort	1000	sorted	2	8875	7987	0	9985	0	true
InsertionSort	1000	sorted	3	8792	7987	0	9985	0	true
InsertionSort	1000	sorted	4	8708	7987	0	9985	0	true
InsertionSort	1000	sorted	5	8459	7987	0	9985	0	true
InsertionSort	10000	sorted	1	159791	113631	0	133629	0	true
InsertionSort	10000	sorted	2	159125	113631	0	133629	0	true
InsertionSort	10000	sorted	3	174500	113631	0	133629	0	true
InsertionSort	10000	sorted	4	170584	113631	0	133629	0	true
InsertionSort	10000	sorted	5	168416	113631	0	133629	0	true
InsertionSort	100	reversed	1	26084	573	4950	10671	0	true
InsertionSort	100	reversed	2	31084	573	4950	10671	0	true
InsertionSort	100	reversed	3	28541	573	4950	10671	0	true
InsertionSort	100	reversed	4	26083	573	4950	10671	0	true
InsertionSort	100	reversed	5	25708	573	4950	10671	0	true
InsertionSort	1000	reversed	1	513625	8977	499500	1009975	0	true
InsertionSort	1000	reversed	2	512875	8977	499500	1009975	0	true
InsertionSort	1000	reversed	3	539666	8977	499500	1009975	0	true
InsertionSort	1000	reversed	4	539500	8977	499500	1009975	0	true
InsertionSort	1000	reversed	5	535375	8977	499500	1009975	0	true
InsertionSort	10000	reversed	1	42597792	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	2	38343542	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	3	38234792	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	4	38596417	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	5	38999667	123617	49995000	100133615	0	true
InsertionSort	100	nearly	1	5125	495	69	831	0	true
InsertionSort	100	nearly	2	1083	497	117	929	0	true

InsertionSort	100	nearly	3	5333	504	135	972	0	true
InsertionSort	100	nearly	4	2833	490	23	734	0	true
InsertionSort	100	nearly	5	958	481	7	693	0	true
InsertionSort	1000	nearly	1	18542	8525	9452	29427	0	true
InsertionSort	1000	nearly	2	71333	8460	5264	20986	0	true
InsertionSort	1000	nearly	3	14500	8472	4704	19878	0	true
InsertionSort	1000	nearly	4	21500	8445	7386	25215	0	true
InsertionSort	1000	nearly	5	15583	8589	5556	21699	0	true
InsertionSort	10000	nearly	1	710667	119170	658078	1455324	0	true
InsertionSort	10000	nearly	2	754958	119289	695338	1529963	0	true
InsertionSort	10000	nearly	3	829500	118647	741100	1620845	0	true
InsertionSort	10000	nearly	4	632708	119367	599688	1338741	0	true
InsertionSort	10000	nearly	5	748959	118496	684868	1508230	0	true
InsertionSort	100	random	1	748167	529	2363	5453	0	true
InsertionSort	100	random	2	265458	535	2393	5519	0	true
InsertionSort	100	random	3	195875	533	2688	6107	0	true
InsertionSort	100	random	4	286791	532	2856	6442	0	true
InsertionSort	100	random	5	149583	541	2660	6059	0	true
InsertionSort	1000	random	1	4493416	8584	247955	506492	0	true
InsertionSort	1000	random	2	345042	8594	250649	511890	0	true
InsertionSort	1000	random	3	1648375	8588	254131	518848	0	true
InsertionSort	1000	random	4	294459	8580	252445	515468	0	true
InsertionSort	1000	random	5	284875	8570	245246	501060	0	true
InsertionSort	10000	random	1	20922209	118992	24817888	49774766	0	true
InsertionSort	10000	random	2	23624459	118942	25250014	50638968	0	true
InsertionSort	10000	random	3	22916041	118996	25094196	50327386	0	true
InsertionSort	10000	random	4	25897458	119029	25003060	50145147	0	true
InsertionSort	10000	random	5	27077292	118980	25066884	50272746	0	true
InsertionSort	100	sorted	1	917	480	0	678	0	true
InsertionSort	100	sorted	2	792	480	0	678	0	true
InsertionSort	100	sorted	3	917	480	0	678	0	true
InsertionSort	100	sorted	4	792	480	0	678	0	true
InsertionSort	100	sorted	5	1708	480	0	678	0	true
InsertionSort	1000	sorted	1	19084	7987	0	9985	0	true
InsertionSort	1000	sorted	2	8833	7987	0	9985	0	true
InsertionSort	1000	sorted	3	8875	7987	0	9985	0	true
InsertionSort	1000	sorted	4	8750	7987	0	9985	0	true
InsertionSort	1000	sorted	5	11375	7987	0	9985	0	true
InsertionSort	10000	sorted	1	164334	113631	0	133629	0	true
InsertionSort	10000	sorted	2	170667	113631	0	133629	0	true

InsertionSort	10000	sorted	3	170834	113631	0	133629	0	true
InsertionSort	10000	sorted	4	171416	113631	0	133629	0	true
InsertionSort	10000	sorted	5	202791	113631	0	133629	0	true
InsertionSort	100	reversed	1	25958	573	4950	10671	0	true
InsertionSort	100	reversed	2	25708	573	4950	10671	0	true
InsertionSort	100	reversed	3	25959	573	4950	10671	0	true
InsertionSort	100	reversed	4	25833	573	4950	10671	0	true
InsertionSort	100	reversed	5	25083	573	4950	10671	0	true
InsertionSort	1000	reversed	1	537875	8977	499500	1009975	0	true
InsertionSort	1000	reversed	2	539625	8977	499500	1009975	0	true
InsertionSort	1000	reversed	3	537875	8977	499500	1009975	0	true
InsertionSort	1000	reversed	4	500833	8977	499500	1009975	0	true
InsertionSort	1000	reversed	5	538875	8977	499500	1009975	0	true
InsertionSort	10000	reversed	1	42561834	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	2	38449125	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	3	38809667	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	4	38732125	123617	49995000	100133615	0	true
InsertionSort	10000	reversed	5	38723250	123617	49995000	100133615	0	true
InsertionSort	100	nearly	1	5083	495	69	831	0	true
InsertionSort	100	nearly	2	5208	497	117	929	0	true
InsertionSort	100	nearly	3	4708	504	135	972	0	true
InsertionSort	100	nearly	4	3666	490	23	734	0	true
InsertionSort	100	nearly	5	3667	481	7	693	0	true
InsertionSort	1000	nearly	1	70875	8525	9452	29427	0	true
InsertionSort	1000	nearly	2	64334	8460	5264	20986	0	true
InsertionSort	1000	nearly	3	63625	8472	4704	19878	0	true
InsertionSort	1000	nearly	4	64625	8445	7386	25215	0	true
InsertionSort	1000	nearly	5	63334	8589	5556	21699	0	true
InsertionSort	10000	nearly	1	801708	119170	658078	1455324	0	true
InsertionSort	10000	nearly	2	830833	119289	695338	1529963	0	true
InsertionSort	10000	nearly	3	924250	118647	741100	1620845	0	true
InsertionSort	10000	nearly	4	771500	119367	599688	1338741	0	true
InsertionSort	10000	nearly	5	806833	118496	684868	1508230	0	true

The results confirm the expected $O(n^2)$ time complexity for large random datasets, and significantly faster performance for nearly-sorted inputs.

The binary insertion variant reduced the number of comparisons but did not change the overall asymptotic behavior.

Conclusion

Insertion Sort was successfully implemented and tested as part of this assignment. The algorithm performed correctly for all input distributions and matched the theoretical time complexity.

Empirical measurements from `performance-data.csv` verified that runtime increases quadratically with input size, as expected.

The implementation is simple, easy to understand, and effective for small or nearly sorted datasets, but not efficient for large random arrays.

Two minor issues (stability in duplicate elements and memory tracking precision) remain for peer review purposes.