A02 - Assignment 2: Constraint Satisfaction Problems

Students:

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Program's solutions

Figure 1: Solution of our program for the easy Sudoku problem.

Figure 2: Solution of our program for the medium Sudoku problem.

Figure 3: Solution of our program for the hard Sudoku problem.

Figure 4: Solution of our program for the very hard Sudoku problem.

```
simonedeidier@dhcp-10-24-147-88 assignment 2 % python3 sudoku.py
Domains before and after ac_3:
                              5,
                {1,
                    2, 3, 4,
                                 6, 7, 8, 9}, after -> {1, 2, 7, 8}
                                    7,
X12: before ->
                       3,
                              5,
                                       8,
                                           9}, after ->
                                 6,
                                                         {1,
                {1,
                    2,
                {1,
                    2, 3, 4,
2, 3, 4,
                              5,
5,
                                 6, 7,
6, 7,
X14: before ->
                                       8, 9}, after ->
                                                         {2,
                                                             6, 7,
                                                                    9}
                                                             3,
X16: before ->
                {1,
                                       8,
                                           9}, after ->
                                                         {2,
                {1,
                                 6,
                                                         {1,
X17: before ->
                       3,
                              5,
                                       8,
                                           9}, after ->
                    2,
                                    7,
                {1,
                    2, 3, 4,
                                 6,
X19: before ->
                                       8, 9}, after ->
                                                         {1,
                    2, 3, 4,
                                           9}, after ->
X22: before ->
                {1,
                              5,
                                 6,
                                       8,
                                                         {1,
                                                             3,
                                 6,
                                    7,
7,
                {1,
X25: before ->
                    2, 3, 4,
                              5,
                                       8,
                                           9}, after ->
                                                         {2,
                                                             3,
                    2,
                              5,
X26: before ->
                {1,
                       3,
                          4,
                                 6,
                                       8,
                                           9}, after ->
                    2,
                {1,
                       3,
                              5,
                                           9}, after ->
X27: before ->
                                 6,
                                       8,
                                                         {1,
                {1,
                    2, 3,
                                 6,
                                       8, 9}, after ->
X28: before ->
                              5,
                                                         {1,
                    2, 3,
                          4,
                              5,
                                    7,
                                           9}, after ->
                                       8,
X29: before ->
                {1,
                                 6,
                       3,
                {1,
                          4,
                    2,
                              5,
                                    7,
                                 6,
                                       8,
                                           9}, after ->
                                                         {2,
X31: before ->
                                    7,
                    2,
                       3,
                          4,
                              5,
                                 6,
                                       8,
                                           9}, after ->
                                                         {3,
X32: before ->
                {1,
X35: before ->
                    2,
                       3,
                              5,
                                 6,
                                       8,
                                           9}, after ->
                                                         {1,
                              5,
5,
                {1,
                                                         {1,
X36: before ->
                    2, 3,
                                 6,
                                           9}, after ->
                                       8,
                                    7,
7,
                {1,
                    2, 3, 4,
                                 6,
                                       8,
                                           9}, after ->
                                                         {1,
                    2, 3, 4,
                              5,
                                 6,
                                       8,
                                           9}, after ->
X42: before ->
                {1,
                                                         {1,
                {1,
                    2, 3, 4,
2, 3, 4,
                             5,
                                 6,
                                    7,
7,
7,
                                           9}, after ->
X43: before ->
                                       8,
                                                         {1,
                       3,
                              5,
X44: before ->
                {1,
                                 6,
                                       8,
                                           9}, after ->
                    2,
                {1,
                       3,
                              5,
                                 6,
                                           9}, after ->
                                                         {1,
X46: before ->
                                       8,
                                    7,
                              5,
                                 6,
X49: before ->
                {1,
                                       8, 9}, after ->
                                                                    6, 7, 8, 9}
                                                         {1,
X52: before ->
                    2,
                              5,
                                           9}, after ->
                {1,
                       3,
                          4,
                                 6,
                                       8,
                                                         {1,
                {1,
                          4,
                              5,
5,
                                 6,
                                    7,
7,
7,
                    2, 3,
X53: before ->
                                       8, 9}, after ->
                                                         {1,
                                                             4, 5,
                       3,
                          4,
X55: before ->
                {1,
                    2,
                                 6,
                                       8,
                                           9}, after ->
                                                         {1,
                    2,
                       3,
X57: before ->
                              5,
                                 6,
                                       8,
                                           9}, after ->
                                                         {1,
                {1,
                    2, 3, 4,
2, 3, 4,
                              5,
                                    7,
7,
                                          9}, after ->
                                                         {1,
X58: before ->
                                 6,
                                       8,
                              5,
                                       8,
                                           9}, after ->
X61: before ->
                {1,
                                 6,
                                                         {1,
                                                             3, 5,
                                                             2,
                                                                          7,
7,
9}
X64: before ->
                    2, 3, 4,
                                    7,
                                       8,
                              5,
                                 6,
                                           9}, after ->
                {1,
                                                         {1,
                                                                             8, 9}
X66: before ->
                {1,
                    2, 3, 4,
                              5,
                                 6,
                                    7,
                                       8,
                                           9}, after ->
                                                         {1,
                    2,
X67: before ->
                {1,
                       3,
                          4,
                              5,
                                 6,
                                    7,
                                       8,
                                           9}, after ->
                                                         {1,
                {1,
                    2, 3,
                              5,
                                                         {1,
X68: before ->
                                 6,
                                          9}, after ->
                                                             2, 3,
                                                                          6,
                                                                             7, 8, 9}
                                       8,
                              5,
                                       8, 9}, after ->
                                 6,
                                                         {1,
                    2,
                          4,
                                       8,
                                           9}, after ->
                              5,
                                 6,
                                                         {1,
X74: before ->
                {1,
                       3,
                                    7,
                                                             2, 3,
                {1,
                              5,
5,
                                 6,
                                    7,
7,
7,
                                       8, 9}, after ->
X75: before ->
                    2, 3,
                          4,
                                                         {1,
                                                             2, 3,
                       3,
                    2,
X78: before ->
                {1,
                          4,
                                 6,
                                       8,
                                           9}, after ->
                                                         {1,
                       3,
X79: before ->
                    2,
                              5,
                                 6,
                                           9}, after ->
                                                         {1,
                                                                          9}
                {1,
                                       8,
                    2, 3, 4,
                              5,
                                 6,
X81: before ->
                {1,
                                       8, 9}, after ->
                                                         {1,
                    2, 3, 4,
                              5,
                                       8, 9}, after ->
X82: before ->
                {1,
                                 6, 7,
                                                         {1,
                                                             2, 3,
                {1,
                    2, 3, 4,
                                       8,
X83: before ->
                              5,
                                 6,
                                    7,
                                          9}, after ->
                                                         {1,
                                                             2,
                {1,
                    2, 3, 4,
                              5,
X84: before ->
                                 6,
                                    7,
                                       8,
                                           9}, after ->
                                                         {1,
                {1,
                    2,
X85: before ->
                       3,
                          4,
                              5,
                                 6,
                                       8,
                                           9}, after ->
                                                         {1,
                             5,
5,
                                 6,
                {1,
                    2, 3, 4,
                                          9}, after ->
                                                         {1,
X88: before ->
                                       8,
                          4,
                       3,
                {1,
                    2,
                                 6,
                                    7,
                                       8,
                                           9}, after ->
                             5,
X93: before ->
                {1,
                    2, 3, 4,
                                 6,
                                    7,
                                       8,
                                           9}, after ->
                                                         {1,
                                                             3,
                                 6,
                                    7,
7,
7,
                {1,
                    2, 3, 4,
                              5,
                                       8,
                                           9}, after ->
                                                         {1,
                                                             3, 4,
X94: before ->
                                                                          8,
                              5,
                    2,
                       3,
                          4,
                                       8,
                                           9}, after ->
                                                         {1,
                                                             3,
X96: before ->
                {1,
                                 6,
                {1, 2, 3, 4, 5, 6, 7, 8, 9}, after -> 
{1, 2, 3, 4, 5, 6, 7, 8, 9}, after ->
                                                         {1,
                                                                3,
X98: before ->
                                                             2,
                                                         {1,
                                                             2, 3,
Reduction in domains: 40.59%
```

Figure 5: Domain values for the unknown variabels before and after the AC3 algorithm for the easy Sudoku problem.

```
simonedeidier@dhcp-10-24-147-88 assignment 2 % python3 sudoku.py
Domains before and after ac_3:
X11: before -> {1, 2, 3, 4, 5, 6, 7, 8, 9}, after -> {2, 5, 6, 7, 8}
X12: before -> {1, 2, 3, 4, 5, 6, 7, 8, 9}, after -> {2, 5, 6, 7, 8}
X13: before -> {1, 2, 3, 4, 5,
                                                            7,
9}
                                6, 7, 8, 9}, after -> {5,
                                                                8}
X14: before ->
                {1,
                    2, 3, 4,
                             5,
                                 6,
                                    7,
                                       8,
                                          9}, after ->
X16: before -> {1,
                          4,
                    2,
                                                            6}
                       3,
                                          9}, after ->
                             5,
                                 6,
                                       8,
X17: before -> \{1, 2, 3, 4, 5,
                                 6, 7,
                                       8, 9}, after
                                                            3, 5, 6}
                                                                  5,
6,
X19: before -> {1, 2, 3, 4, 5,
                                6,
                                       8,
                                          9}, after ->
                                   7,
                                                                      6, 8, 9}
X22: before -> {1,
                    2, 3, 4, 5,
                                    7,
                                       8,
                                          9}, after ->
                                                                      8}
                                6,
                                                        {2,
X25: before -> {1,
                    2, 3, 4, 5, 6,
                                       8, 9}, after
                                                     ->
                    2,
                          4, 5,
X26: before -> {1,
                       3,
                                       8,
                                          9}, after
X27: before ->
               {1,
                                6,
                                       8, 9}, after ->
                    2, 3, 4, 5,
X28: before -> {1, 2, 3, 4, 5,
                                       8, 9}, after
                                                                      6, 8, 9}
                                6,
                                    7,
                    2, 3, 4, 5,
X29: before -> {1,
                                6,
                                    7,
                                       8,
                                          9}, after ->
                                                                      6,
                                                                         8,
                                                                            9}
               {1,
                                    7,
                                                                   6}
X31: before ->
                    2, 3, 4, 5,
                                6,
                                       8,
                                          9}, after ->
X32: before ->
                {1,
                    2, 3, 4, 5,
                                6,
                                       8,
                                          9}, after
                          4,
X33: before ->
                {1,
                    2,
                       3,
                             5,
                                 6,
                                       8,
                                          9}, after ->
X37: before ->
                                       8,
                                                        {1,
               {1,
                                          9}, after ->
                                                            3, 4, 5, 6}
                    2, 3, 4, 5,
X39: before -> {1, 2, 3, 4, 5, 6, 7, 8, 9}, after ->
                                                            2, 4, 5, 6, 8, 9}
                    2, 3, 4, 5,
                                       8, 9}, after ->
X41: before -> {1,
                                6, 7,
X42: before -> {1,
                                       8,
                                6,
                    2, 3, 4, 5,
                                   7,
                                          9}, after ->
               {1,
X45: before ->
                    2, 3, 4, 5,
                                 6,
                                    7,
                                          9}, after
X49: before -> {1,
                    2,
                                          9}, after ->
                       3,
                          4, 5,
                                                                5, 6, 8}
                                 6,
                                       8,
               {1,
                                6,
X52: before ->
                    2, 3, 4, 5,
                                       8, 9}, after
                                                                8}
X54: before -> {1,
                    2, 3, 4, 5,
                                       8, 9}, after ->
                                    7,
                                6,
X56: before -> {1,
                    2, 3, 4, 5,
                                          9}, after ->
                                    7,
                                       8,
                                                                   6,
                                                        {1,
                                                                   4,
X58: before -> {1,
                                                               3,
                    2, 3, 4, 5,
                                       8,
                                          9}, after
                                                        {1,
                                6,
                                   7,
                                                                         6, 8}
X61: before ->
                {1,
                    2,
                       3,
                          4,
                             5,
                                       8,
                                          9}, after ->
X65: before ->
                                          9}, after ->
                {1,
                    2,
                       3, 4,
                             5,
                                       8,
                                   7,
                                                                         6, 7, 8,
7, 8, 9}
X68: before -> {1, 2, 3, 4, 5,
                                6,
                                       8, 9}, after ->
                                                                                   9}
X69: before -> \{1, 2, 3, 4, 5,
                                   7, 8, 9}, after ->
                                6,
                                                        {1,
X71: before -> {1,
                                6,
                    2, 3, 4, 5,
                                       8, 9}, after ->
                                    7,
                                                        {2,
                                   7,
X73: before -> {1,
                    2, 3, 4, 5,
                                6,
                                       8, 9}, after
                                                     ->
                    2,
X77: before -> {1,
                          4, 5,
                                    7,
                                          9}, after ->
                       3,
                                 6,
                                       8,
                                       8,
X78: before ->
                                                                      6,
               {1,
                    2, 3, 4, 5,
                                 6,
                                          9}, after ->
                                                                             9}
                                   7,
                                                                             9}
X79: before ->
               {1, 2, 3, 4, 5, 6,
                                       8, 9}, after ->
X81: before -> {1,
                    2, 3, 4, 5, 6, 7, 8, 9}, after ->
                                                                      8}
                                6,
               {1,
X82: before ->
                    2, 3, 4, 5,
                                    7,
                                       8, 9}, after ->
                                                        {1,
                {1,
X83: before ->
                    2,
                       3, 4,
                             5,
                                 6,
                                    7,
                                       8,
                                          9}, after ->
                                                         {1,
                                          9}, after ->
X84: before ->
                {1,
                    2,
                       3,
                             5,
                                 6,
                                       8,
                                       8, 9}, after ->
                                6,
X85: before -> {1, 2, 3, 4, 5,
X88: before -> {1, 2, 3, 4, 5, 6, 7, 8, 9}, after ->
X91: before -> {1,
                    2, 3, 4, 5,
                                6, 7, 8, 9}, after -> {1,
X93: before -> {1,
                    2, 3, 4, 5, 6, 7,
                                       8, 9}, after -> {1,
                                                                                9}
                    2, 3, 4, 5,
                                    7,
X94: before ->
               {1,
                                       8,
                                          9}, after ->
X96: before ->
                                          9}, after ->
               {1,
                    2, 3, 4, 5,
                                                        {1,
                                6,
                                    7,
                                       8,
               {1,
                                                        {1,
                    2, 3, 4, 5, 6, 7,
                                       8, 9}, after ->
X97: before ->
                                                            2,
X98: before -> {1, 2, 3, 4, 5, 6, 7, 8, 9}, after -> {1, 2, X99: before -> {1, 2, 3, 4, 5, 6, 7, 8, 9}, after -> {1, 2,
Reduction in domains: 39.12%
```

Figure 6: Domain values for the unknown variabels before and after the **AC3** algorithm for the medium Sudoku problem.

```
simonedeidier@dhcp-10-24-147-88 assignment 2 % python3 sudoku.py
Domains before and after ac_3:
X12: before -> \{1, 2, 3, 4, 5,
                                6, 7, 8, 9}, after -> {1, 3, 5, 6, 8}
                          4,
                             5,
                                6,
                                   7, 8,
                                          9}, after ->
                                          9}, after ->
                                                                  6,
X16: before -> {1, 2,
                      3,
                         4,
                             5,
                                6,
                                      8,
                                                           2,
                                                                     9}
                                                        {1,
               {1,
X17: before ->
                    2,
                      3,
                          4,
                             5,
                                6,
                                   7,
                                      8,
                                          9}, after
                                          9}, after ->
               {1,
                       3, 4,
                             5,
                                                                     9}
X18: before ->
                    2,
                                6,
                                   7,
                                      8,
X21: before -> \{1, 2, 3, 4,
                             5, 6, 7, 8,
                                          9}, after ->
                                6,
                                          9}, after ->
                             5,
X22: before -> {1, 2, 3, 4,
                                   7, 8,
                                                            2,
                                                        {1,
X23: before -> {1, 2, 3, 4, 5, 6, 7,
                                      8,
                                          9}, after
                    2,
                                          9}, after ->
X24: before ->
                       3, 4,
                             5,
                                6,
                                   7,
                                      8,
               {1,
X26: before -> {1,
                   2, 3, 4,
2, 3, 4,
                             5, 6, 7,
                                      8,
                                          9}, after ->
X27: before -> {1,
                             5,
                                          9}, after ->
                                6, 7, 8,
X28: before -> {1,
                    2, 3, 4,
                             5, 6,
                                          9}, after
                                      8,
                                                        {1,
                                                                        9}
                       3, 4,
                                   7,
                                          9}, after ->
X29: before ->
                {1,
                    2,
                             5,
                                6,
                                      8,
X31: before -> {1,
                                   7, 8,
                                          9}, after ->
                    2, 3, 4,
                             5, 6,
                             5,
                                          9}, after ->
X32: before -> {1, 2, 3, 4,
                                6, 7, 8,
X35: before -> {1,
                                                                  8,
                                      8,
                    2, 3, 4,
                             5,
                                6,
                                          9}, after ->
                                                                     9}
                                                        {2,
                                                            5,
                      3, 4,
                             5,
X36: before ->
                {1,
                    2,
                                6,
                                   7,
                                      8,
                                          9}, after ->
                                                               6,
                                   7,
                                          9}, after ->
               {1,
                    2,
                       3, 4,
                             5, 6,
                                                                     7, 8, 9
X38: before ->
                                      8,
X41: before -> {1, 2, 3, 4, X42: before -> {1, 2, 3, 4,
                             5, 6, 7, 8,
                                          9}, after ->
                             5,
                                6,
                                      8,
                                          9}, after ->
                                                            2,
                                                                  8}
                                                        {1,
                {1,
                             5,
X43: before ->
                    2, 3, 4,
                                6,
                                   7,
                                      8,
                                          9}, after ->
X45: before ->
                            5,
                                          9}, after ->
               {1,
                      3, 4,
                   2,
                                6,
                                   7,
                                      8,
                                                        {2,
                                                                  5, 7, 8,
5, 7, 8}
5, 7, 9}
8, 9}
X48: before \rightarrow \{1, 2, 3, 4, 5, 6, 7, 8,
                                          9}, after ->
                             5,
                                      8,
                                          9}, after ->
                                                        {1, 3,
X49: before -> {1, 2, 3, 4,
                                6,
X53: before -> {1,
                                   7,
                   2, 3, 4,
                             5,
                                6,
                                      8,
                                          9}, after ->
                                                            3,
                                          9}, after ->
X54: before -> {1,
                    2,
                       3, 4,
                             5,
                                6,
                                      8,
X55: before -> {1,
                   2, 3, 4,
                             5, 6,
                                          9}, after ->
                                      8,
X56: before -> {1,
                                          9}, after ->
                   2, 3, 4,
                             5,
                                6, 7,
                                      8,
X57: before -> {1,
                    2, 3, 4,
                             5, 6,
                                      8,
                                          9}, after
                                                            3,
                                                                     9}
                                                        {1,
X61: before ->
                {1,
                    2,
                       3, 4,
                             5,
                                6,
                                   7,
                                      8,
                                          9}, after ->
X62: before -> {1,
                   2, 3, 4,
                             5, 6,
                                   7, 8,
                                          9}, after ->
X65: before -> {1, 2, 3, 4,
                             5, 6, 7, 8,
                                          9}, after ->
                                                        {2,
X67: before -> {1,
                                          9}, after ->
                    2, 3, 4,
                             5,
                                6,
                                   7,
                                      8,
                                                        {1,
                                                            2,
                                                                           9}
7,
7,
                       3, 4,
                             5,
                                          9}, after ->
X68: before -> {1,
                    2,
                                6,
                                   7,
                                      8,
X69: before -> {1,
                            5, 6, 7,
5, 6, 7,
                                          9}, after ->
                    2,
                       3, 4,
                                      8,
                                                                        6,
                                                                               8}
X72: before -> {1, 2, 3, 4, X74: before -> {1, 2, 3, 4,
                                          9}, after ->
                                      8,
                             5,
                                6,
                                      8,
                                          9}, after ->
                                                        {2,
                {1,
                             5,
X75: before ->
                    2,
                       3, 4,
                                6,
                                   7,
                                      8,
                                          9}, after ->
                                   7,
               {1,
                             5,
                                          9}, after ->
X78: before ->
                   2,
                      3, 4,
                                6,
                                      8,
                                                        {1,
X79: before -> {1, 2, 3, 4, 5, 6, 7, 8,
                                          9}, after ->
                             5,
                                      8,
                                          9}, after ->
X81: before -> {1, 2, 3, 4,
                                6,
                                   7,
                                                        {3,
X82: before -> {1,
                                      8,
                    2, 3, 4,
                             5,
                                6,
                                   7,
                                          9}, after ->
X83: before -> {1,
                                6,
                    2,
                       3, 4,
                             5,
                                      8,
                                          9}, after ->
X84: before -> {1,
                   2, 3, 4,
                             5, 6, 7,
                                          9}, after ->
                                      8,
X86: before -> {1,
                                6,
                                          9}, after ->
                   2, 3, 4,
                             5,
                                      8,
X87: before -> {1,
                             5, 6,
                                          9}, after
                    2, 3, 4,
                                      8,
                                                        {1,
                                                                            8}
X88: before -> {1,
                    2,
                       3, 4,
                             5,
                                6,
                                   7,
                                      8,
                                          9}, after ->
X89: before -> {1,
                                          9}, after ->
                                                        {1,
                   2, 3, 4,
                             5, 6,
                                      8,
X92: before -> {1, 2, 3, 4,
                             5,
                                          9}, after ->
                                6,
                                   7,
                                      8,
                                                        {1,
X93: before -> {1,
                   2, 3, 4,
                             5, 6,
                                   7,
                                      8,
                                          9}, after -> {1,
                                                           2,
                       3, 4,
X94: before ->
               {1,
                   2,
                             5,
                                6,
                                   7,
                                      8,
                                          9}, after ->
                             5, 6,
5, 6,
                                          9},
                                                           2,
X96: before ->
               {1,
                   2,
                       3, 4,
                                              after ->
                                                       {1,
                                      8,
                                                               3,
                   2, 3,
                          4,
                                6, 7, 8,
                                          9},
                                              after ->
                                                       {1,
                                                           2,
Reduction in domains: 37.11%
```

Figure 7: Domain values for the unknown variabels before and after the AC3 algorithm for the hard Sudoku problem.⁵

```
simonedeidier@dhcp-10-24-147-88 assignment 2 % python3 sudoku.py
Domains before and after ac_3:
                                                                         5,
                                                                                       7, 8, 9}, after ->
                                                 2,
                                                                 4,
                                       {1,
                                                                                6,
                                                2,
2,
                                                         3, 4,
3, 4,
                                                                         5,
                                                                                6,
 X12: before ->
                                       {1,
                                                                         5,
                                       {1,
                                                                                6,
                                      {1, 2,
{1, 2,
                                                        3, 4,
3, 4,
                                                                               6,
                                                                                                                                                            8,
7,
                                                                                                                                                                    9}
8,
                                                                         5,
X15: before ->
                                                                                                                                            {5,
X17: before ->
                                                                        5,
                                                                                6,
                                                                        5,
                                                        3, 4,
3, 4,
                                                2,
                                                                                                                                                                             9}
X18: before -> {1,
                                                                                6,
                                                2,
X19: before ->
                                       {1,
                                                                        5,
                                                                                6,
                                                        3, 4,
3, 4,
                                                                        5,
X22: before
                                                                                6,
                                       {1,
                                                2,
                                                                        5,
                                                                                6,
                                                                                                                                           {1,
X23: before ->
                                       {1,
X25: before
                                                         3, 4,
                                                                        5,
                                                                                6,
                                                                       5,
                                                2,
                                                        3, 4,
3, 4,
X26: before ->
                                       {1,
                                                                                                                                                                            8}
                                                                                6,
X28: before ->
                                       {1,
                                                                        5,
                                                                                6,
                                                                                                                                           {1,
                                                        3, 4,
3, 4,
 X29: before ->
                                                 2,
                                       {1,
                                                                        5,
                                                                                6,
                                                                                                                                           {2,
                                                                                                                                                                             8,
                                                                                                                                                                                    9}
                                               2,
X31: before ->
                                                                        5,
                                       {1,
                                                                                6,
                                                                                                                                           {1,
X32: before
                                                         3, 4,
                                                                         5,
                                                                                6,
                                       {1,
                                                 2,
                                                         3, 4,
                                                                        5,
X33: before ->
                                                                                6,
                                                                                                                                                                            9}
                                                                                                                                           {1,
                                       {1,
X34: before
                                       {1,
                                                 2,
                                                         3, 4,
                                                                        5,
                                                                                6,
                                      {1, 2, 
{1, 2,
                                                        3, 4,
3, 4,
                                                                               6,
                                                                                                                                           {1,
X36: before ->
                                                                        5,
 X37: before -> {1,
                                                                        5,
                                                                                6,
                                                                                                                                           {1,
                                                        3, 4,
3, 4,
                                                                        5,
X43: before -> {1,
                                                 2,
                                                                                6,
                                                                                                                                           {1,
                                                2,
                                                                        5,
5,
X44: before ->
                                                                                6,
                                                                                                                                           {2,
                                       {1,
                                                        3, 4,
3, 4,
3, 4,
                                               2, 2, 2,
 X47: before
                                                                                6,
                                                                        5,
X48: before ->
                                                                                6,
                                                                                                                                                    2,
                                                                                                                                           {1,
                                       {1,
                                                                        5,
X49: before
                                       {1,
                                                                                6,
                                                                                                                                            {2,
                                                                                                                                                                                     9}
                                                                       5,
                                      {1, 2, 
{1, 2, 
{1, 2, 
{1, 2,
                                                        3, 4,
3, 4,
X51: before ->
                                                                                6,
X52: before -> {1,
                                                                        5,
                                                                                6,
                                                                                                                                           {1,
                                                        3, 4,
3, 4,
 X53: before ->
                                                                        5,
                                                                                6,
                                                2,
                                                                        5,
5,
X54: before ->
                                                                                6,
                                                                                                                                                                             9}
                                                                                                                                           {2,
                                       {1,
 X55: before
                                                         3, 4,
                                                                                6,
                                                                        5,
                                                2,
2,
                                                        3, 4,
3, 4,
 X56: before ->
                                                                                6,
                                                                                                                                            {2,
                                                                                                                                                                     8}
                                       {1,
X57: before ->
                                       {1,
                                                                        5,
                                                                                6,
                                                                       5,
                                                        3, 4,
3, 4,
                                                                                6,
                                                2,
                                                                                                                                           {2,
                                                                                                                                                                            7,
7,
6,
X63: before ->
                                       {1,
                                                                                                                                                                                     9}
                                                                                                                                                                                   8,
7,
7,
X64: before -> {1,
                                                2,
                                                                                                                                                    3,
                                                                        5,
                                                                                6,
                                                                                                                                           {2,
                                                 2,
                                                                                        7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 7, 8, 
                                                                                                        9}, after
X67: before
                                       {1,
                                                         3, 4,
                                                                        5,
                                                                                6,
                                                                                                                                                                                            8,
                                                                        5,
5,
X68: before ->
                                                2,
                                                         3, 4,
                                                                                                        9}, after
                                                                                                                                                     2,
                                                                                                                                                                                             8,
                                       {1,
                                                                                                                                                                                                    9}
                                                                                6,
                                                                                                                                  ->
                                                                                                                                           {1,
 X69: before
                                                         3, 4,
                                                                                6,
                                                                                                        9}, after
                                                                                                                                                                                             8,
                                                2,
2,
                                                        3, 4,
3, 4,
                                                                                                                                                            6,
                                                                                                                                                                    9}
9}
X71: before ->
                                                                        5,
                                                                                6,
                                                                                                        9}, after
                                      {1,
                                                                                                                                           {3,
                                                                        5,
                                                                                                        9}, after ->
X72: before ->
                                       {1,
                                                                                6,
                                                                                                                                           {3,
                                                                       5,
                                                        3, 4,
3, 4,
                                       {1, 2,
                                                                                                       9}, after ->
X73: before ->
                                                                                6,
                                                                                                                                           {3,
                                                2,
2,
2,
                                                                                                                                                                    7,
6,
7,
X74: before -> {1,
                                                                                                        9}, after ->
                                                                        5,
                                                                                6,
                                                                                                                                           {3,
 X76: before
                                                         3, 4,
                                                                        5,
                                                                                6,
                                                                                                        9}, after
                                       {1,
X77: before ->
                                       {1,
                                                         3, 4,
                                                                        5,
                                                                                6,
                                                                                                        9}, after
                                                                                                                                  ->
                                                                                                                                           {3,
                                                        3, 4,
                                                                        5,
 X82: before
                                       {1,
                                                 2,
                                                                                6,
                                                                                                        9}, after
                                                                                                                                            {3,
                                                2,
2,
                                                        3, 4,
3, 4,
X83: before -> {1,
                                                                        5,
                                                                                6,
                                                                                                        9}, after
                                                                                                                                            {3,
                                                                                                                                                                                    7,
7,
6,
X85: before ->
                                       {1,
                                                                        5,
                                                                                6,
                                                                                                        9}, after ->
                                                2,
2,
2,
                                                                       5,
5,
                                                        3, 4,
3, 4,
                                                                                6,
X86: before ->
                                                                                                        9}, after
                                       {1,
X88: before -> {1,
                                                                                6,
                                                                                                        9}, after ->
                                                                                                                                            {1,
                                                                                                                                                                                                           9}
                                                        3, 4,
X89: before
                                       {1,
                                                                        5,
                                                                                6,
                                                                                                        9}, after
                                                                                                                                                                                                    8,
                                                                                                                                                                                                           9}
                                               2,
                                                         3, 4,
                                                                                6,
                                                                                                                                           {1,
X91: before ->
                                       {1,
                                                                        5,
                                                                                                        9}, after
                                                                                                                                  ->
                                                 2,
                                                         3, 4,
                                                                         5,
                                                                                                        9},
 X92: before ->
                                       {1,
                                                                                6,
                                                                                                                   after
                                                                                                                                           {1,
                                                2,
2,
                                                                4,
                                                                                                                                                    2,
                                                        3,
 X94: before -> {1,
                                                                        5,
                                                                                6,
                                                                                                        9}, after
                                                                                                                                           {1,
                                                         3, 4,
                                                                                                                                                             3,
X95: before ->
                                                                        5,
                                                                                6,
                                                                                                        9}, after ->
                                       {1,
                                                                                                                                           {1,
                                                2,
                                                        3, 4,
                                                                                6,
                                                                                        7,
7,
 X97: before ->
                                                                         5,
                                                                                                8,
                                                                                                        9}, after
                                                                                                                                           {1,
                                                                                                                                                            3,
                                       {1,
                                                                                                                                                    2,
                                                                                                                                                             3,
 X98: before ->
                                                         3, 4,
                                                                        5,
                                                                                6,
                                                                                                8,
                                                                                                        9}, after ->
                                                                                                                                                                                     6,
                                                                                                                                           {1,
                                       {1,
 X99: before ->
                                       {1, 2, 3, 4,
                                                                        5,
                                                                                6, 7, 8, 9}, after
                                                                                                                                           {1, 2, 3,
 Reduction in domains: 34.95%
```

Figure 8: Domain values for the unknown variabels before and after the AC3 algorithm for the very hard Sudoku problem.

Domains

backtrack() calls

Backtrack calls: 326
Backtrack failures: 244

Figure 9: Count of calls of the backtrack() function and count of failures for the easy Sudoku.

Backtrack calls: 2165 Backtrack failures: 2083

Figure 10: Count of calls of the backtrack() function and count of failures for the medium Sudoku.

Backtrack calls: 1288 Backtrack failures: 1206

Figure 11: Count of calls of the backtrack() function and count of failures for the hard Sudoku.

Runtime of the backtracking search algorithm, AC-3 and total runtime

Discussion of the results

The AC-3 algorithm drastically reduces the total runtime when solving some Sudoku problems, especially in more complex configurations, due to its ability to efficiently prune the search space by enforcing arc-consistency early in the process. In simpler terms, AC-3 eliminates values from variable domains that

Backtrack calls: 14382 Backtrack failures: 14300

Figure 12: Count of calls of the backtrack() function and count of failures for the very hard Sudoku.

```
Runtime of AC-3 algorithm: 0.0180 seconds
Runtime of backtracking search algorithm: 0.0143 seconds
Total runtime of AC-3 and backtracking search algorithms: 0.0324 seconds
```

Figure 13: Runtime of both the backtrack() * and AC-3 algorithm, with also the total runtime, for the easy Sudoku.*

```
Runtime of AC-3 algorithm: 0.0161 seconds
Runtime of backtracking search algorithm: 0.0713 seconds
Total runtime of AC-3 and backtracking search algorithms: 0.0874 seconds
```

Figure 14: Runtime of both the backtrack() * and AC-3 algorithm, with also the total runtime, for the medium Sudoku.*

```
Runtime of AC-3 algorithm: 0.0189 seconds
Runtime of backtracking search algorithm: 0.0575 seconds
Total runtime of AC-3 and backtracking search algorithms: 0.0764 seconds
```

Figure 15: Runtime of both the backtrack() * and AC-3 algorithm, with also the total runtime, for the hard Sudoku.*

```
Runtime of AC-3 algorithm: 0.0177 seconds
Runtime of backtracking search algorithm: 0.6175 seconds
Total runtime of AC-3 and backtracking search algorithms: 0.6351 seconds
```

Figure 16: Runtime of both the backtrack() * and AC-3 algorithm, with also the total runtime, for the very hard Sudoku.*

are inconsistent with their neighboring constraints, which simplifies the problem before more computationally expensive search algorithms, such as **backtracking**, are applied.

For easier Sudoku puzzles, fewer constraints lead to quicker reductions, as there are more obvious domain eliminations. However, even in more complex configurations, the algorithm still cuts down unnecessary branches of the search tree, speeding up the solving process by reducing the number of possible variable assignments the solver needs to explore. This pre-processing step significantly lowers the runtime in cases where otherwise the problem would involve a larger number of constraint checks or deep recursive searches.

The backtracking algorithm, on the other hand, is a depth-first search algorithm that incrementally builds candidates to the solutions and abandons a candidate ("backtracks") as soon as it determines that the candidate cannot possibly be completed to a valid solution. While backtracking is powerful and can solve many problems, it can be slow for large and complex problems due to its exhaustive nature. However, when combined with AC-3, the search space is significantly reduced, making backtracking more efficient and faster in finding solutions. In summary, the combination of these two algorithms leverages the strengths of both: the pre-processing efficiency of AC-3 and the exhaustive search capability of backtracking.