

CSP-Solver

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1 Main Page

1.1 CSP-Solver

Project for the lecture "Objektorientierte Programmierung mit C++" at Ulm University. Solves arbitrary binary constraint satisfaction problems (CSP) using the [AC-3 algorithm](#) and backtracking search. The seminar paper (German) for this project can be found [here](#).

1.1.1 Doxygen Documentation

- [HTML](#)
- [PDF](#)

1.1.2 How To

A CPS consists of a set of variables, represented by `csp::Variable` and a set of constraints (dependencies between pairs of variables) represented by `csp::Constraint` or `csp::Arc`. You can use your own variable type by deriving from `csp::Variable`.

1.1.2.1 Creating Variables To create a variable, a domain of values has to be given, representing all possible values the variable might take:

```
#include "csp_solver.h"
csp::Variable a{1, 2, 17, 24};
```

A variable can be defined on any domain type. Also, you can change the underlying container used for the domain:

```
#include "csp_solver.h"
#include <vector>
using MyVar = csp::Variable<double, std::vector>;
MyVar a{0.2, 4, 1.7};
```

The default container used as domain storage is `std::list`. This is due to the fact that during solving, values need to be erased from the domain. When your variables have domains with many values, a data storage that supports efficient removal from any position might be advantageous. When your domains only contain a few values (and / or when your values can be copied / moved efficiently), a container like `std::vector` or `std::deque` which supports efficient iteration might be the better choice.

Furthermore, you can create your own variable type. This allows you to add functionality to your variable type. For example, you can add a variable name:

```
#include <string>
#include "csp_solver.h"
class MyVar : public csp::Variable<int> {
public:
    explicit MyVar(std::string name) : csp::Variable<int>{1, 2, 3, 4}, name(std::move(name)) {}
    const std::string name;
};
```

1.1.2.2 Specifying Constraints `csp::Constraint` or `csp::Arc` specify dependencies between pairs of variables. They contain a pointer type to each variable and a binary predicate specifying the constraint. You can use arbitrary pointer types that support the dereference-operator as well as `->` operator. Example using the custom variable type above and `shared_ptr` (which I recommend over raw pointers):

```
#include <memory>
#include "csp_solver.h"
auto varA = std::make_shared<MyVar>("A");
auto varB = std::make_shared<MyVar>("B");
csp::Constraint aLessB(varA, varB, std::less<>());
```

You can also use `csp::Arc` to specify the relation between variables. The difference is, that an arc describes a directed constraint. Even if $A < B$ is equivalent to $B > A$, two arcs describing both relations respectively are not. When defining your CSP using arcs, make sure that always both directions are specified explicitly. When using `csp::Constraint` only one direction suffices. In some situations, it is easier to specify the CSP using arcs than using constraints or vice versa. You cannot mix arcs and constraints when creating a CSP but you can convert a `csp::Constraint` to two equivalent `csp::Arc`.

1.1.2.3 Creating the CSP Once you specified all variables and the respective constraints, create your CSP using:

```
csp::Csp myCsp = csp::make_csp(std::array{varA, varB}, std::array{aLessB});
```

You can use arbitrary containers that support iteration.

1.1.2.4 Solving the CSP An instance of `csp::Csp` can be solved using:

```
bool success = csp::solve(myCsp);
```

If solving the CSP is possible all domains of all variables will be reduced to exactly one value. The algorithm will find a solution if one exists (given enough time). If multiple exist, it is unspecified which exact solution is found. If the CSP cannot be solved, the function returns `false` but might still modify the variables' value domains.

1.1.2.4.1 Specifying a Solving Strategy By default, `csp::solve` uses the minimum remaining values strategy, meaning that the algorithm chooses the variable with the fewest remaining values in its domain to be assigned next. You can also use a different (even custom) strategy e.g.:

```
auto strat = [] (const auto & problem) {
    // Your code here -> return the desired unassigned variable from the CSP
    return theNextVar;
};
bool success = csp::solve(myCsp, strat);
```

Examples on how to create your own strategy can be found in the file `src/strategies.h`.

1.1.3 Solving Sudoku Puzzles

The `src/main.cpp` contains a program that can solve Sudoku puzzles. A Sudoku is defined by a grid of numbers where a 0 indicates, that the respective field is yet to be assigned. Some examples are provided in the `res` directory.

2 Namespace Documentation

2.1 csp Namespace Reference

Contains all relevant datastructures and functions for defining and solving a constraint satisfaction problem.

Namespaces

- [strategies](#)
contains different variable choosing strategies that can be used to solve a CSP. Apart from these strategies, custom strategies can be used. A strategy must return one of the pointers to a variable stored in the given CSP.
- [util](#)
contains utility functions used by the search algorithm

Data Structures

- class [Arc](#)
- class [Constraint](#)
- struct [Csp](#)
- class [Variable](#)

Typedefs

- `template<typename T >`
`using BinaryPredicate = std::function< bool(const T &, const T &)>`

Functions

- `template<typename VarPtr , typename Strategy = strategies::Mrv<VarPtr>>
bool solve (Csp< VarPtr > &problem, const Strategy &strategy=Strategy())`
- `template<typename VarContainer , typename ArcContainer , std::enable_if_t< type_traits::is_arc< std::remove_reference_t<
decltype(*std::begin(std::declval< ArcContainer >()))>>::value , int >
auto make_csp (const VarContainer &variables, const ArcContainer &arcs) -> Csp< std::decay_t<
decltype(std::end(arcs), std::end(variables), *std::begin(variables))>>`
- `template<typename VarContainer , typename ConstraintContainer , std::enable_if_t< type_traits::is_constraint< std::remove_↵
reference_t< decltype(*std::begin(std::declval< ConstraintContainer >()))>>::value , int >
auto make_csp (const VarContainer &variables, const ConstraintContainer &constraints) -> Csp< std↵
::decay_t< decltype(std::end(constraints), std::end(variables), *std::begin(variables))>>`
- `template<typename VarIt , typename ConstrIt , std::enable_if_t< type_traits::is_constraint< std::remove_reference_↵
t< decltype(*std::declval< ConstrIt >())>>::value , int >
auto make_csp (VarIt vBegin, VarIt vEnd, ConstrIt cBegin, ConstrIt cEnd) -> Csp< std::decay_t<
decltype(++cBegin, cBegin==cEnd,++vBegin, vBegin==vEnd, *vBegin)>>`
- `template<typename VarIt , typename ArcIt , std::enable_if_t< type_traits::is_arc< std::remove_reference_t< decltype(*std::declval<
ArcIt >())>>::value , int >
auto make_csp (VarIt vBegin, VarIt vEnd, ArcIt aBegin, ArcIt aEnd) -> Csp< std::decay_t< decltype(++a↵
Begin, aBegin==aEnd,++vBegin, vBegin==vEnd, *vBegin)>>`

2.1.1 Detailed Description

Contains all relevant datastructures and functions for defining and solving a constraint satisfaction problem.

2.1.2 Function Documentation

2.1.2.1 make_csp() [1/4] `template<typename VarContainer , typename ArcContainer , std::enable_↵
_if_t< type_traits::is_arc< std::remove_reference_t< decltype(*std::begin(std::declval< Arc↵
Container >()))>>::value , int >
auto csp::make_csp (
 const VarContainer & variables,
 const ArcContainer & arcs) -> Csp<std::decay_t<decltype(std::end(arcs), std↵
::end(variables), *std::begin(variables))>>`

Creates a CSP from a container of variable-pointer and a container of `csp::Arcs`

Template Parameters

<i>VarContainer</i>	Container-Type containing pointer-types to a type derived of <code>csp::Variable</code>
<i>ArcContainer</i>	Container-Type containing <code>csp::Arcs</code>

Parameters

<i>variables</i>	Container of all variables in the CSP
<i>arcs</i>	Container of all directed <code>csp::Arcs</code> in the CSP

Returns

[csp::Csp](#) representing the problem induced by the given variables and arcs

Note

When using [csp::Arcs](#) to specify the constraints, make sure that if you have a constraint e.g. $A < B$, you specify both [csp::Arcs](#) representing $A < B$ and $B > A$! Otherwise the problem is malformed and may lead to invalid solutions!

2.1.2.2 make_csp() [2/4] `template<typename VarContainer , typename ConstraintContainer , std::enable_if_t< type_traits::is_constraint< std::remove_reference_t< decltype(*std::begin(std::declval< ConstraintContainer >()))>>::value , int >`
`auto csp::make_csp (`
`const VarContainer & variables,`
`const ConstraintContainer & constraints) -> Csp<std::decay_t<decltype(std::end(constraints), std::end(variables), *std::begin(variables))>>`

Creates a CSP from a container of variable-pointers and a container of [csp::Constraints](#)

Template Parameters

<i>VarContainer</i>	Container-Type containing pointer-types to a type derived of csp::Variable
<i>ArcContainer</i>	Container-Type containing csp::Constraints

Parameters

<i>variables</i>	Container of all variables in the CSP
<i>arcs</i>	Container of all undirected csp::Constraints in the CSP

Returns

[csp::Csp](#) representing the problem induced by the given variables and constraints

Note

When using [csp::Constraints](#) to specify the constraints, specify them only once. A [csp::Constraint](#) for e.g. $A < B$ fully represents the constraint between the [csp::Variable](#) A and B. Specifying $A < B$ and $B > A$ may lead to performance loss during search!

2.1.2.3 make_csp() [3/4] `template<typename VarIt , typename ArcIt , std::enable_if_t< type_traits::is_arc< std::remove_reference_t< decltype(*std::declval< ArcIt >())>>::value , int >`
`auto csp::make_csp (`
`VarIt vBegin,`
`VarIt vEnd,`
`ArcIt aBegin,`

```
ArcIt aEnd ) -> Csp<std::decay_t<decltype(++aBegin, aBegin == aEnd, ++vBegin,  
vBegin == vEnd, *vBegin)>>
```

Creates a CSP from a container of variable-pointers and a container of `csp::Arc` using iterators. Variables and arcs are taken from the respective range [begin, end)

Template Parameters

<i>Var</i> ↔ <i>It</i>	Iterator type of variable container
<i>Arc</i> ↔ <i>It</i>	Iterator type of arc container

Parameters

<i>vBegin</i>	start of range of variables
<i>vEnd</i>	end of range of variables (exclusive)
<i>aBegin</i>	start of range of arcs
<i>aEnd</i>	start of range of arcs (exclusive)

Returns

[csp::Csp](#) representing the problem induced by the given variables and arcs

Note

When using [csp::Arcs](#) to specify the constraints, make sure that if you have a constraint e.g. $A < B$, you specify both [csp::Arcs](#) representing $A < B$ and $B > A$! Otherwise the problem is malformed and may lead to invalid solutions!

2.1.2.4 make_csp() [4/4] `template<typename VarIt , typename ConstrIt , std::enable_if_t<type_traits::is_constraint< std::remove_reference_t< decltype(*std::declval< ConstrIt >())>>::value , int >::value , int > auto csp::make_csp (VarIt vBegin, VarIt vEnd, ConstrIt cBegin, ConstrIt cEnd) -> Csp<std::decay_t<decltype(++cBegin, cBegin == cEnd, ++v↔Begin, vBegin == vEnd, *vBegin)>>`

Creates a CSP from a container of variable-pointers and a container of [csp::Constraint](#) using iterators. Variables and constraints are taken from the respective range [begin, end)

Template Parameters

<i>VarIt</i>	Iterator type of variable container
<i>Constr</i> ↔ <i>It</i>	Iterator type of constraint container

Parameters

<i>vBegin</i>	start of range of variables
<i>vEnd</i>	end of range of variables (exclusive)
<i>cBegin</i>	start of range of constraints

Parameters

<i>cEnd</i>	start of range of constraints (exclusive)
-------------	---

Returns

[csp::Csp](#) representing the problem induced by the given variables and constraints

Note

When using [csp::Constraints](#) to specify the constraints, specify them only once. A [csp::Constraint](#) for e.g. $A < B$ fully represents the constraint between the [csp::Variable](#) A and B. Specifying $A < B$ and $B > A$ may lead to performance loss during search!

```
2.1.2.5 solve()  template<typename VarPtr , typename Strategy = strategies::Mrv<VarPtr>>
bool csp::solve (
    Csp< VarPtr > & problem,
    const Strategy & strategy = Strategy() )
```

Solves a CSP. If a solution exists, the value domains of each variable in the given [Csp](#) will be reduced to exactly one value. If multiple solutions exist, it is unspecified which is found. If no solution exists, false is returned but the value domains of the variables might still be altered

Template Parameters

<i>VarPtr</i>	Pointer-type to a type derived from csp::Variable
<i>Strategy</i>	Type of value selection strategy during search (default: minimum remaining values strategy). Has to provide ()-Operator and return VarPtr from given csp::Csp

Parameters

<i>problem</i>	CSP to be solved
----------------	------------------

Returns

True if problem was solved, false otherwise

2.2 csp::strategies Namespace Reference

contains different variable choosing strategies that can be used to solve a CSP. Apart from these strategies, custom strategies can be used. A strategy must return one of the pointers to a variable stored in the given CSP.

Data Structures

- struct [First](#)
- struct [Mrv](#)

2.2.1 Detailed Description

contains different variable choosing strategies that can be used to solve a CSP. Apart from these strategies, custom strategies can be used. A strategy must return one of the pointers to a variable stored in the given CSP.

2.3 csp::util Namespace Reference

contains utility functions used by the search algorithm

Typedefs

- `template<typename VarT >`
using **CspCheckpoint** = `std::vector< typename VarT::DomainT >`

Functions

- `template<typename VarPtr, typename Strategy >`
`bool recursiveSolve (Csp< VarPtr > &problem, const Strategy &strategy)`
- `template<typename VarPtr >`
`bool removeInconsistent (const Arc< VarPtr > &arc)`
- `template<typename VarPtr >`
`bool ac3 (Csp< VarPtr > &problem)`
- `template<typename VarPtr >`
`auto makeCspCheckpoint (const Csp< VarPtr > &problem) -> CspCheckpoint< typename Csp< VarPtr >::VarT >`
- `template<typename VarPtr >`
`void restoreCspFromCheckpoint (Csp< VarPtr > &problem, const CspCheckpoint< typename Csp< VarPtr >::VarT > &checkpoint)`

2.3.1 Detailed Description

contains utility functions used by the search algorithm

2.3.2 Function Documentation

2.3.2.1 ac3() `template<typename VarPtr >`
`bool csp::util::ac3 (`
 `Csp< VarPtr > & problem)`

Obtains arc consistency in a CSP using the AC3-algorithm

Template Parameters

<i>VarPtr</i>	Pointer-type to a type derived from <code>csp::Variable</code>
---------------	--

Parameters

<i>problem</i>	The CSP to be processed
----------------	-------------------------

Returns

True if arc consistency was obtained, false if not possible

```
2.3.2.2 makeCspCheckpoint()  template<typename VarPtr >
auto csp::util::makeCspCheckpoint (
    const Csp< VarPtr > & problem ) -> CspCheckpoint<typename Csp<VarPtr>::VarT>
```

Backs up all value domains of all variables in a CSP

Template Parameters

<i>VarPtr</i>	Pointer-type to a type derived from csp::Variable
---------------	---

Parameters

<i>problem</i>	The CSP to be backed up
----------------	-------------------------

Returns

vector of [csp::Variable](#) domains. Domains are ordered according to the variables in the CSP

```
2.3.2.3 recursiveSolve()  template<typename VarPtr , typename Strategy >
bool csp::util::recursiveSolve (
    Csp< VarPtr > & problem,
    const Strategy & strategy )
```

Recursive backtracking search for [csp::Csps](#). Prefer using the wrapper function [csp::solve](#)

Template Parameters

<i>VarPtr</i>	Pointer-type to a type derived from csp::Variable
<i>Strategy</i>	Type of value selection strategy during search

Parameters

<i>problem</i>	CSP to be solved
<i>strategy</i>	value selection strategy object used during during search

Returns

True if problem was solved, false otherwise

2.3.2.4 removeInconsistent() `template<typename VarPtr >`

```
bool csp::util::removeInconsistent (
    const Arc< VarPtr > & arc )
```

Removes all inconsistent values from the source node of the given `csp::Arc`. As a result, the source node's value domain only contains values for which a valid value in the domain of the destination node exists.

Template Parameters

<code>VarPtr</code>	Pointer-type to a type derived from <code>csp::Variable</code>
---------------------	--

Parameters

<code>arc</code>	<code>Arc</code> to be processed
------------------	----------------------------------

Returns

True if the value domain of the source node was modified, false otherwise

2.3.2.5 restoreCspFromCheckpoint() `template<typename VarPtr >`

```
void csp::util::restoreCspFromCheckpoint (
    Csp< VarPtr > & problem,
    const CspCheckpoint< typename Csp< VarPtr >::VarT > & checkpoint )
```

Restores the value domains of all `csp::Variables` in a CSP from the given checkpoint

Template Parameters

<code>VarPtr</code>	Pointer-type to a type derived from <code>csp::Variable</code>
---------------------	--

Parameters

<code>problem</code>	The CPS to be restored
<code>checkpoint</code>	Checkpoint to load the value domains from

3 Data Structure Documentation

3.1 `csp::Arc< VarPtr >` Class Template Reference

```
#include <Arc.h>
```

Public Types

- using **VarType** = typename [Constraint](#)< VarPtr >::VarType

Public Member Functions

- [Arc](#) (VarPtr v1, VarPtr v2, BinaryPredicate< VarType > predicate, bool [reverse](#)=false) noexcept([Constraint](#)< VarPtr >::nothrow_constructible)
- constexpr void [reverse](#) () noexcept
- constexpr VarPtr [from](#) () const noexcept
- constexpr VarPtr [to](#) () const noexcept
- bool [constraintSatisfied](#) (const VarType &valFrom, const VarType &valTo) const

3.1.1 Detailed Description

```
template<typename VarPtr>
class csp::Arc< VarPtr >
```

Represents a binary constraint as directed arc in a constraint satisfaction problem. Is mainly used during solving to obtain arc consistency

Template Parameters

<i>VarPtr</i>	Pointer-type to a type derived from csp::Variable
---------------	---

Note

Constraints implicitly specify two directed arcs. For example: A constraint $A < B$ is equivalent to two arcs $A < B$ and $B > A$

3.1.2 Constructor & Destructor Documentation

```
3.1.2.1 Arc()  template<typename VarPtr >
csp::Arc< VarPtr >::Arc (
    VarPtr v1,
    VarPtr v2,
    BinaryPredicate< VarType > predicate,
    bool reverse = false ) [inline], [noexcept]
```

Ctor

Parameters

<i>v1</i>	Pointer-Type to first variable
<i>v2</i>	Pointer-Type to first variable
<i>predicate</i>	Constraint in form of a binary predicate
<i>reverse</i>	Specifies whether the arc represents $v2 \rightarrow v1$ instead

3.1.3 Member Function Documentation

3.1.3.1 `constraintSatisfied()` `template<typename VarPtr >`

```
bool csp::Arc< VarPtr >::constraintSatisfied (
    const VarType & valFrom,
    const VarType & valTo ) const [inline]
```

Checks if the binary constraint between source and destination is satisfied. If values are chosen from the domains of `from()` and `to()` respectively, makes sure the constraint predicate is evaluated correctly

Parameters

<i>valFrom</i>	value of the source node
<i>valTo</i>	value of the destination node

Returns

true if constraint is satisfied, false otherwise

3.1.3.2 `from()` `template<typename VarPtr >`

```
constexpr VarPtr csp::Arc< VarPtr >::from ( ) const [inline], [constexpr], [noexcept]
```

Gets the source node of the arc

Returns

Always returns the pointer to the source node of the arc, taking into account if the arc is reversed

3.1.3.3 `reverse()` `template<typename VarPtr >`

```
constexpr void csp::Arc< VarPtr >::reverse ( ) [inline], [constexpr], [noexcept]
```

Reverses the arc (switches `from()` and `to()` members)

3.1.3.4 `to()` `template<typename VarPtr >`

```
constexpr VarPtr csp::Arc< VarPtr >::to ( ) const [inline], [constexpr], [noexcept]
```

Gets the destination node of the arc

Returns

Always returns the pointer to the destination node of the arc, taking into account if the arc is reversed

The documentation for this class was generated from the following file:

- `src/Arc.h`

3.2 csp::Constraint< VarPtr > Class Template Reference

```
#include <Arc.h>
```

Public Types

- using **VarType** = typename std::remove_reference_t< decltype(*std::declval< VarPtr >())>::ValueT
- using **ArcT** = [Arc](#)< VarPtr >

Public Member Functions

- [Constraint](#) (VarPtr v1, VarPtr v2, BinaryPredicate< VarType > predicate) noexcept(nothrow_constructible)
- auto [getArcs](#) () const -> std::pair< [ArcT](#), [ArcT](#) >

Protected Attributes

- VarPtr **var1**
- VarPtr **var2**
- BinaryPredicate< VarType > **predicate**

Static Protected Attributes

- static constexpr bool **nothrow_constructible**

3.2.1 Detailed Description

```
template<typename VarPtr>
class csp::Constraint< VarPtr >
```

Represents a binary undirected constraint in a constraint satisfaction problem

Template Parameters

<i>VarPtr</i>	Pointer-type to a type derived from csp::Variable
---------------	---

3.2.2 Constructor & Destructor Documentation

3.2.2.1 Constraint() `template<typename VarPtr >`
`csp::Constraint< VarPtr >::Constraint (`
 VarPtr v1,
 VarPtr v2,
 BinaryPredicate< VarType > predicate) [inline], [noexcept]

Ctor

Parameters

<i>v1</i>	Pointer-Type to first variable
<i>v2</i>	Pointer-Type to first variable
<i>predicate</i>	Constraint in form of a binary predicate

3.2.3 Member Function Documentation

3.2.3.1 getArcs() `template<typename VarPtr >`
`auto csp::Constraint< VarPtr >::getArcs () const -> std::pair<ArcT, ArcT> [inline]`

Create the two equivalent directed csp::Arcs

Returns

Pair of equivalent csp::Arcs

3.2.4 Field Documentation

3.2.4.1 nothrow_constructible `template<typename VarPtr >`
`constexpr bool csp::Constraint< VarPtr >::nothrow_constructible [static], [constexpr], [protected]`

Initial value:

```
= std::is_nothrow_move_constructible_v<VarPtr> &&
    std::is_nothrow_move_constructible_v<BinaryPredicate <
        VarType>
```

The documentation for this class was generated from the following file:

- src/[Arc.h](#)

3.3 csp::Csp< VarPtr > Struct Template Reference

```
#include <Csp.h>
```

Public Types

- using **ArcT** = [Arc](#)< VarPtr >
- using **VarT** = std::remove_reference_t< decltype(*std::declval< VarPtr >())>
- using **VarListT** = std::vector< VarPtr >
- using **ArcListT** = std::deque< [ArcT](#) >
- using **NeighbourListT** = std::unordered_map< VarPtr, std::vector< [ArcT](#) > >

Data Fields

- const VarListT **variables**
- const ArcListT **arcs**
- const NeighbourListT **incomingNeighbours**

Friends

- template<typename VarIt , typename ArcIt , std::enable_if_t< type_traits::is_arc< std::remove_reference_t< decltype(*std::declval< ArcIt >())>>::value >
auto [make_csp](#) (VarIt vBegin, VarIt vEnd, ArcIt aBegin, ArcIt aEnd) -> [Csp](#)< std::decay_t< decltype(*++aBegin, aBegin==aEnd, ++vBegin, vBegin==vEnd, *vBegin)>>

3.3.1 Detailed Description

```
template<typename VarPtr>
struct csp::Csp< VarPtr >
```

Represents a constraint satisfaction problem (CSP)

Template Parameters

<i>VarPtr</i>	VarPtr Pointer-type to a type derived from csp::Variable
---------------	--

3.3.2 Friends And Related Function Documentation

3.3.2.1 make_csp template<typename VarPtr >
template<typename VarIt , typename ArcIt , std::enable_if_t< type_traits::is_arc< std::remove_←
_reference_t< decltype(*std::declval< ArcIt >())>>::value >
auto make_csp (
 VarIt vBegin,
 VarIt vEnd,
 ArcIt aBegin,
 ArcIt aEnd) -> [Csp](#)<std::decay_t<decltype(*++aBegin, aBegin == aEnd, ++vBegin,
vBegin == vEnd, *vBegin)>> [friend]

Creates a CSP from a container of variable-pointers and a container of [csp::Arc](#) using iterators. Variables and arcs are taken from the respective range [begin, end)

Template Parameters

<i>Var← It</i>	Iterator type of variable container
<i>Arc← It</i>	Iterator type of arc container

Parameters

<i>vBegin</i>	start of range of variables
<i>vEnd</i>	end of range of variables (exclusive)
<i>aBegin</i>	start of range of arcs
<i>aEnd</i>	start of range of arcs (exclusive)

Returns

`csp::Csp` representing the problem induced by the given variables and arcs

Note

When using `csp::Arcs` to specify the constraints, make sure that if you have a constraint e.g. $A < B$, you specify both `csp::Arcs` representing $A < B$ and $B > A$! Otherwise the problem is malformed and may lead to invalid solutions!

The documentation for this struct was generated from the following file:

- `src/Csp.h`

3.4 `csp::strategies::First< VarPtr >` Struct Template Reference

```
#include <strategies.h>
```

Public Member Functions

- `VarPtr operator()` (const `Csp< VarPtr >` &problem) const

3.4.1 Detailed Description

```
template<typename VarPtr>
struct csp::strategies::First< VarPtr >
```

`Variable` selection strategy that simply chooses the next unassigned variable

Template Parameters

<i>VarPtr</i>	Pointer-type to a type derived from <code>csp::Variable</code>
---------------	--

The documentation for this struct was generated from the following file:

- `src/strategies.h`

3.5 `csp::type_traits::is_arc< T >` Struct Template Reference

```
#include <Csp.h>
```

Inherits `declval< T >`.

3.5.1 Detailed Description

```
template<typename T>
struct csp::type_traits::is_arc< T >
```

Used to check if type is of template type [csp::Arc](#)

Template Parameters

<i>T</i>	Type to be checked
----------	--------------------

The documentation for this struct was generated from the following file:

- [src/Csp.h](#)

3.6 `csp::type_traits::is_constraint< T >` Struct Template Reference

```
#include <Csp.h>
```

Static Public Attributes

- static constexpr bool **value**

3.6.1 Detailed Description

```
template<typename T>
struct csp::type_traits::is_constraint< T >
```

Used to check if type is of template type [csp::Constraint](#)

Template Parameters

<i>T</i>	Type to be checked
----------	--------------------

3.6.2 Field Documentation

```
3.6.2.1 value template<typename T >
constexpr bool csp::type_traits::is_constraint< T >::value [static], [constexpr]
```

Initial value:

```
= decltype(implementations::constraintTest(std::declval<T>()))::value
    && ! is_arc<T>::value
```

The documentation for this struct was generated from the following file:

- src/[Csp.h](#)

3.7 csp::type_traits::is_dereferencable< T > Struct Template Reference

```
#include <Arc.h>
```

Inherits declval< T >.

3.7.1 Detailed Description

```
template<typename T>
struct csp::type_traits::is_dereferencable< T >
```

Used to check if type can be dereferenced using *-Operator

Template Parameters

<i>T</i>	Type to be checked
----------	--------------------

The documentation for this struct was generated from the following file:

- src/[Arc.h](#)

3.8 csp::type_traits::is_derived_from_var< T > Struct Template Reference

```
#include <Arc.h>
```

Inherits declval< std::remove_reference_t< T > * >.

3.8.1 Detailed Description

```
template<typename T>
struct csp::type_traits::is_derived_from_var< T >
```

Used to check if type is derived from [csp::Variable](#)

Template Parameters

<i>T</i>	Type to be checked
----------	--------------------

The documentation for this struct was generated from the following file:

- src/[Arc.h](#)

3.9 csp::strategies::Mrv< VarPtr > Struct Template Reference

```
#include <strategies.h>
```

Public Member Functions

- VarPtr **operator()** (const [Csp](#)< VarPtr > &problem) const

3.9.1 Detailed Description

```
template<typename VarPtr>
struct csp::strategies::Mrv< VarPtr >
```

Minimum remaining values strategy for variable selection during search. Chooses the variable with the fewest remaining possible values

Template Parameters

<i>VarPtr</i>	Pointer-type to a type derived from csp::Variable
---------------	---

The documentation for this struct was generated from the following file:

- src/[strategies.h](#)

3.10 csp::Variable< T, DomainType > Class Template Reference

```
#include <Variable.h>
```

Inherited by SudokuNode.

Public Types

- using **DomainT** = DomainType< T >
- using **ValueT** = T

Public Member Functions

- [Variable](#) (DomainT domain)
- [Variable](#) (std::initializer_list< T > init)
- void [assign](#) (T val)
- constexpr bool [isAssigned](#) () const noexcept(noexcept(std::declval< DomainT >().size()))
- template<typename Container , std::enable_if_t< std::is_convertible_v< decltype(*std::begin(std::declval< Container >())), T > , int >
> void [setValueDomain](#) (const Container &container)
- void [setValueDomain](#) (DomainT values)
- constexpr auto [valueDomain](#) () const noexcept -> const DomainT &
- constexpr auto [valueDomain](#) () noexcept -> DomainT &

3.10.1 Detailed Description

```
template<typename T, template< typename... > typename DomainType = std::list>
class csp::Variable< T, DomainType >
```

Represents a variable in a constraint satisfaction problem

Template Parameters

<i>T</i>	Type of the contained value
<i>DomainType</i>	Type of container used for the variables domain (default is std::list)

3.10.2 Constructor & Destructor Documentation

3.10.2.1 Variable() [1/2] `template<typename T , template< typename... > typename DomainType = std::list>
csp::Variable< T, DomainType >::Variable (
 DomainT domain) [inline], [explicit]`

CTOR

Parameters

<i>domain</i>	list of possible values
---------------	-------------------------

3.10.2.2 Variable() [2/2] `template<typename T , template< typename... > typename DomainType = std::list>
csp::Variable< T, DomainType >::Variable (
 std::initializer_list< T > init) [inline]`

CTOR using initializer list

Parameters

<i>init</i>	
-------------	--

3.10.3 Member Function Documentation

3.10.3.1 assign() `template<typename T , template< typename... > typename DomainType = std::list>::list>
void csp::Variable< T, DomainType >::assign (
 T val) [inline]`

Sets the variable to the specified value (by reducing the value domain to said value)

Parameters

<i>val</i>	The desired value
------------	-------------------

Note

The value does not have to be in the variable's value domain. No checks are performed.

3.10.3.2 isAssigned() `template<typename T , template< typename... > typename DomainType = std::list>
constexpr bool csp::Variable< T, DomainType >::isAssigned () const [inline], [constexpr],
[noexcept]`

Checks if the variable is assigned

Returns

True if the variable's domain contains exactly one value, false otherwise

3.10.3.3 setValueDomain() [1/2] `template<typename T , template< typename... > typename DomainType = std::list>
template<typename Container , std::enable_if_t< std::is_convertible_v< decltype(*std::begin(std::declval< Container >())) , T > , int >
void csp::Variable< T, DomainType >::setValueDomain (
 const Container & container) [inline]`

Sets the value domain accepting arbitrary containers that support iteration

Template Parameters

<i>Container</i>	Type of the container
------------------	-----------------------

Parameters

<i>container</i>	desired values
------------------	----------------

Note

Avoid duplicates! No checks are performed. Duplicates can lead to performance losses.

3.10.3.4 `setValueDomain()` [2/2] `template<typename T , template< typename... > typename DomainType = std::list>`
`void csp::Variable< T, DomainType >::setValueDomain (`
`DomainT values) [inline]`

Sets the value domain

Parameters

<i>values</i>	desired values.
---------------	-----------------

Note

Avoid duplicates! No checks are performed. Duplicates can lead to performance losses.

3.10.3.5 `valueDomain()` [1/2] `template<typename T , template< typename... > typename DomainType = std::list>`
`constexpr auto csp::Variable< T, DomainType >::valueDomain () const -> const DomainT& [inline],`
`[constexpr], [noexcept]`

Gets the value domain

Returns

```

3.10.3.6 valueDomain() [2/2] template<typename T , template< typename... > typename Domain←
Type = std::list>
constexpr auto csp::Variable< T, DomainType >::valueDomain ( ) -> DomainT & [inline], [constexpr],
[noexcept]

```

Gets the value domain

Returns

The documentation for this class was generated from the following file:

- [src/Variable.h](#)

4 File Documentation

4.1 src/Arc.h File Reference

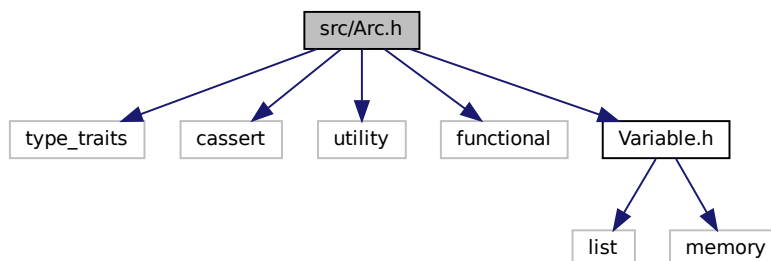
This file contains the the [csp::Arc](#) and the [csp::Constraint](#) class. Both can be used to specify constraints (dependencies) between two [csp::Variable](#) pointers. An Arc is directed (specifying a constraint that a Variable X X imposes on a Variable Y, e.g. $A < B$ but not $B > A$). A Constraint implicitly defines both directions (e.g. if $A < B \Leftrightarrow B > A$). The actual constraint is given as a binary predicate.

```

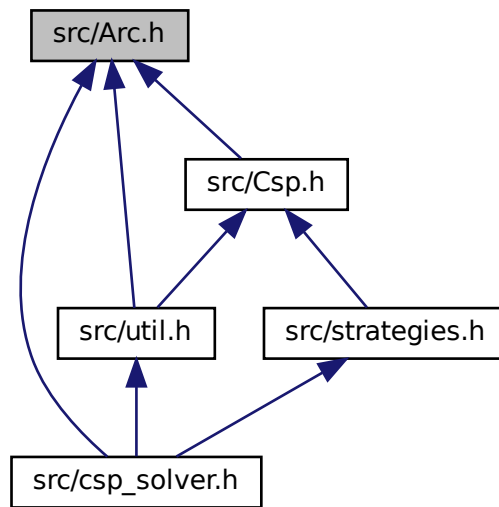
#include <type_traits>
#include <cassert>
#include <utility>
#include <functional>
#include "Variable.h"

```

Include dependency graph for Arc.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct `csp::type_traits::is_dereferencable< T >`
- struct `csp::type_traits::is_derived_from_var< T >`
- class `csp::Arc< VarPtr >`
- class `csp::Constraint< VarPtr >`
- class `csp::Arc< VarPtr >`

Namespaces

- `csp`
Contains all relevant datastructures and functions for defining and solving a constraint satisfaction problem.

Typedefs

- `template<typename T >`
using `csp::BinaryPredicate` = `std::function< bool(const T &, const T &)>`

Functions

- `template<typename T >`
`std::true_type csp::type_traits::implementations::pointerTest (decltype(*std::declval< T >()), std::declval< T >())`
- `template<typename T >`
`std::false_type csp::type_traits::implementations::pointerTest (...)`
- `template<typename VarType, template<typename... >typename Domain>`
`std::true_type csp::type_traits::implementations::derivedTest (Variable< VarType, Domain > *)`
- `std::false_type csp::type_traits::implementations::derivedTest (...)`

4.1.1 Detailed Description

This file contains the `csp::Arc` and the `csp::Constraint` class. Both can be used to specify constraints (dependencies) between two `csp::Variable` pointers. An Arc is directed (specifying a constraint that a Variable X imposes on a Variable Y, e.g. $A < B$ but not $B > A$). A Constraint implicitly defines both directions (e.g. if $A < B \Leftrightarrow B > A$). The actual constraint is given as a binary predicate.

Author

Tim Luchterhand

Date

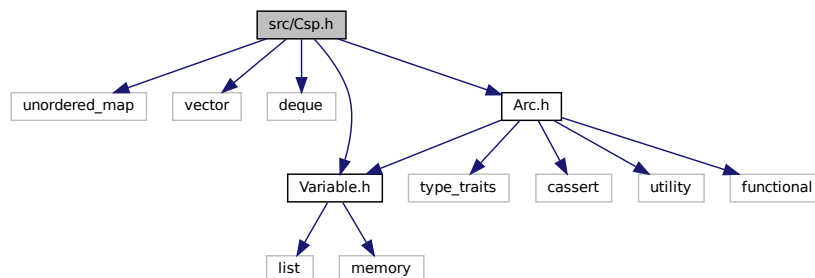
22.07.20

4.2 src/Csp.h File Reference

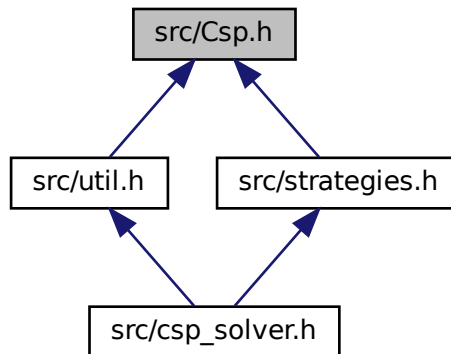
This file contains the `csp::Csp` class which represents a complete definition of a constraint satisfaction problem. The class contains a list of Variable pointers, a list of all arcs and a map that specifies incoming arcs of each variable. The `csp::Csp` should be created using the provided function `csp::make_csp`.

```
#include <unordered_map>
#include <vector>
#include <deque>
#include "Variable.h"
#include "Arc.h"
```

Include dependency graph for Csp.h:



This graph shows which files directly or indirectly include this file:



Data Structures

- struct [csp::type_traits::is_arc< T >](#)
- struct [csp::type_traits::is_constraint< T >](#)
- struct [csp::Csp< VarPtr >](#)

Namespaces

- [csp](#)

Contains all relevant datastructures and functions for defining and solving a constraint satisfaction problem.

Functions

- `template<typename VarPtr >`
`std::true_type csp::type_traits::implementations::arcTest (Arc< VarPtr >)`
- `std::false_type csp::type_traits::implementations::arcTest (...)`
- `template<typename VarPtr >`
`std::true_type csp::type_traits::implementations::constraintTest (Constraint< VarPtr >)`
- `std::false_type csp::type_traits::implementations::constraintTest (...)`
- `template<typename VarContainer , typename ArcContainer , std::enable_if_t< type_traits::is_arc< std::remove_reference_t< decltype(*std::begin(std::declval< ArcContainer >()))>>::value , int >`
`auto csp::make_csp (const VarContainer &variables, const ArcContainer &arcs) -> Csp< std::decay_t< decltype(std::end(arcs), std::end(variables), *std::begin(variables))>>`
- `template<typename VarContainer , typename ConstraintContainer , std::enable_if_t< type_traits::is_constraint< std::remove_reference_t< decltype(*std::begin(std::declval< ConstraintContainer >()))>>::value , int >`
`auto csp::make_csp (const VarContainer &variables, const ConstraintContainer &constraints) -> Csp< std::decay_t< decltype(std::end(constraints), std::end(variables), *std::begin(variables))>>`
- `template<typename VarIt , typename ConstrIt , std::enable_if_t< type_traits::is_constraint< std::remove_reference_t< decltype(*std::declval< ConstrIt >())>>::value , int >`
`auto csp::make_csp (VarIt vBegin, VarIt vEnd, ConstrIt cBegin, ConstrIt cEnd) -> Csp< std::decay_t< decltype(++cBegin, cBegin==cEnd, ++vBegin, vBegin==vEnd, *vBegin)>>`
- `template<typename VarIt , typename ArcIt , std::enable_if_t< type_traits::is_arc< std::remove_reference_t< decltype(*std::declval< ArcIt >())>>::value , int >`
`auto csp::make_csp (VarIt vBegin, VarIt vEnd, ArcIt aBegin, ArcIt aEnd) -> Csp< std::decay_t< decltype(++aBegin, aBegin==aEnd, ++vBegin, vBegin==vEnd, *vBegin)>>`

4.2.1 Detailed Description

This file contains the `csp::Csp` class which represents a complete definition of a constraint satisfaction problem. The class contains a list of Variable pointers, a list of all arcs and a map that specifies incoming arcs of each variable. The `csp::Csp` should be created using the provided function `csp::make_csp`.

Author

Tim Luchterhand

Date

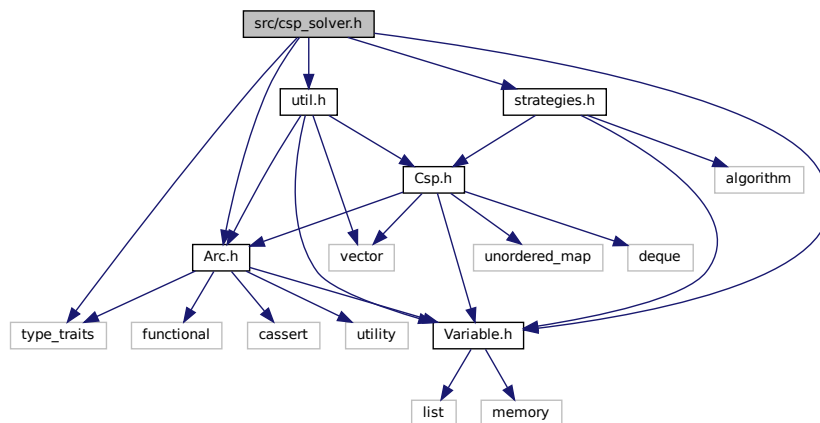
25.07.20

4.3 src/csp_solver.h File Reference

This file contains the solving algorithm for CSPs. It consists of a recursive backtracking search which repeatedly uses the AC-3 algorithm to reduce the search space. Use the `csp::solve` wrapper method.

```
#include <type_traits>
#include "Variable.h"
#include "Arc.h"
#include "util.h"
#include "strategies.h"
```

Include dependency graph for `csp_solver.h`:



Namespaces

- `csp`
Contains all relevant datastructures and functions for defining and solving a constraint satisfaction problem.
- `csp::util`
contains utility functions used by the search algorithm

Functions

- `template<typename VarPtr , typename Strategy >`
`bool csp::util::recursiveSolve (Csp< VarPtr > &problem, const Strategy &strategy)`
- `template<typename VarPtr , typename Strategy = strategies::Mrv<VarPtr>>`
`bool csp::solve (Csp< VarPtr > &problem, const Strategy &strategy=Strategy())`

4.3.1 Detailed Description

This file contains the solving algorithm for CSPs. It consists of a recursive backtracking search which repeatedly uses the AC-3 algorithm to reduce the search space. Use the `csp::solve` wrapper method.

Author

Tim Luchterhand

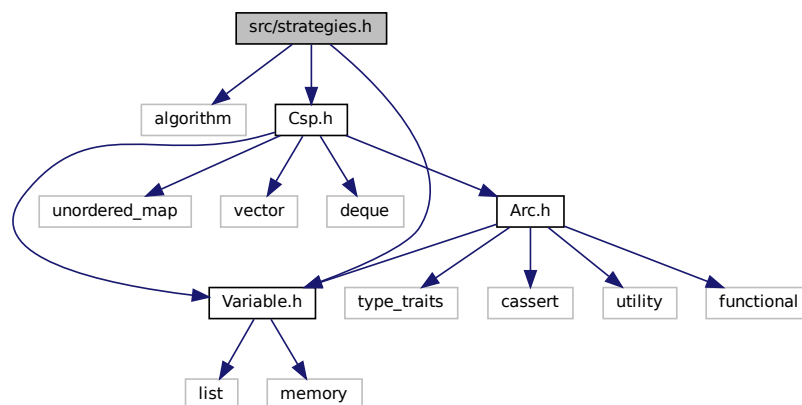
Date

25.07.20

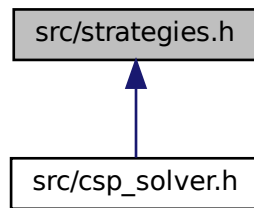
4.4 src/strategies.h File Reference

This file contains different variable choosing strategies that can be used to solve a CSP. Apart from these strategies, custom strategies can be used. A strategy must return one of the pointers to a variable stored in the given CSP.

```
#include <algorithm>
#include "Csp.h"
#include "Variable.h"
Include dependency graph for strategies.h:
```



This graph shows which files directly or indirectly include this file:



Data Structures

- struct `csp::strategies::Mrv`< VarPtr >
- struct `csp::strategies::First`< VarPtr >

Namespaces

- `csp`
Contains all relevant datastructures and functions for defining and solving a constraint satisfaction problem.
- `csp::strategies`
contains different variable choosing strategies that can be used to solve a CSP. Apart from these strategies, custom strategies can be used. A strategy must return one of the pointers to a variable stored in the given CSP.

4.4.1 Detailed Description

This file contains different variable choosing strategies that can be used to solve a CSP. Apart from these strategies, custom strategies can be used. A strategy must return one of the pointers to a variable stored in the given CSP.

Author

Tim Luchterhand

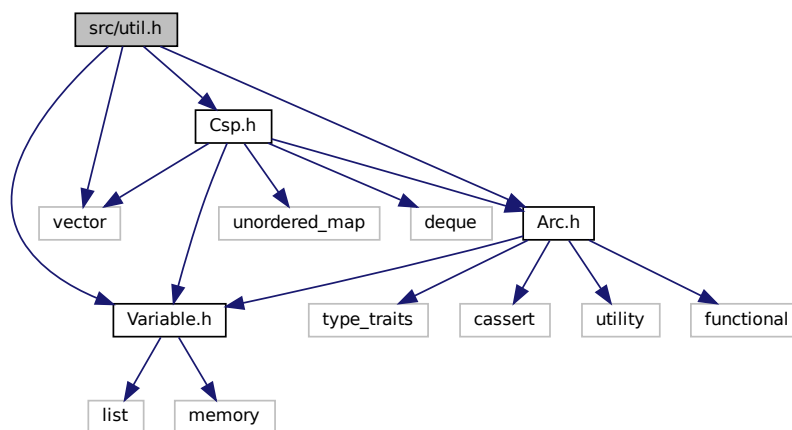
Date

25.07.20

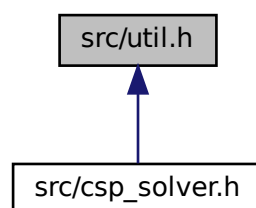
4.5 src/util.h File Reference

This file contains utility functions used by the search algorithm.

```
#include <vector>
#include "Variable.h"
#include "Arc.h"
#include "Csp.h"
Include dependency graph for util.h:
```



This graph shows which files directly or indirectly include this file:



Namespaces

- `csp`
Contains all relevant datastructures and functions for defining and solving a constraint satisfaction problem.
- `csp::util`
contains utility functions used by the search algorithm

Typedefs

- `template<typename VarT >`
`using csp::util::CspCheckpoint = std::vector< typename VarT::DomainT >`

Functions

- `template<typename VarPtr >`
`bool csp::util::removeInconsistent (const Arc< VarPtr > &arc)`
- `template<typename VarPtr >`
`bool csp::util::ac3 (Csp< VarPtr > &problem)`
- `template<typename VarPtr >`
`auto csp::util::makeCspCheckpoint (const Csp< VarPtr > &problem) -> CspCheckpoint< typename Csp< VarPtr >::VarT >`
- `template<typename VarPtr >`
`void csp::util::restoreCspFromCheckpoint (Csp< VarPtr > &problem, const CspCheckpoint< typename Csp< VarPtr >::VarT > &checkpoint)`

4.5.1 Detailed Description

This file contains utility functions used by the search algorithm.

Author

Tim Luchterhand

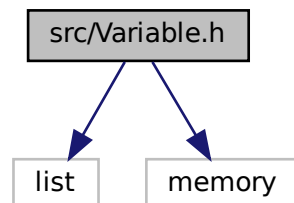
Date

11.07.20

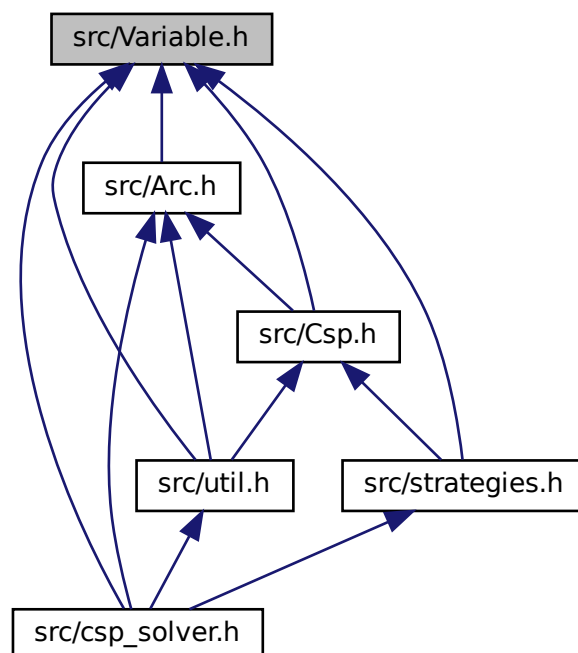
4.6 src/Variable.h File Reference

This file contains the definition of a variable which is used to describe a CSP. Custom variable types can be used by deriving from [csp::Variable](#).

```
#include <list>
#include <memory>
Include dependency graph for Variable.h:
```



This graph shows which files directly or indirectly include this file:



Data Structures

- class `csp::Variable< T, DomainType >`

Namespaces

- `csp`

Contains all relevant datastructures and functions for defining and solving a constraint satisfaction problem.

4.6.1 Detailed Description

This file contains the definition of a variable which is used to describe a CSP. Custom variable types can be used by deriving from `csp::Variable`.

Author

Tim Luchterhand

Date

11.07.20

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