

Introduction

This lack of transparency of modern machine learning models like deep neural networks exacerbates a number of other problems typically associated with them: they tend to be unstable [?], encode existing biases [?] and learn representations that are surprising or even counter-intuitive from a human perspective [?]. Nonetheless, they often form the basis for data-driven decision-making systems in real-world applications.

As others have pointed out, this scenario gives rise to an undesirable principal-agent problem involving a group of principals - i.e. human stakeholders - that fail to understand the behaviour of their agent - i.e. the black-box system [?]. The group of principals may include programmers, product managers and other decision-makers who develop and operate the system as well as those individuals ultimately subject to the decisions made by the system. In practice, decisions made by black-box systems are typically left unchallenged since the principals cannot scrutinize them:

“You cannot appeal to (algorithms). They do not listen. Nor do they bend.” [?]

In light of all this, a quickly growing body of literature on explainable artificial intelligence (XAI) has emerged. Counterfactual Explanations (CE) fall into this broader category. They can help human stakeholders make sense of the systems they develop, use or endure: they explain how inputs into a system need to change for it to produce different decisions. Explainability benefits internal as well as external quality assurance. Explanations that involve realistic and actionable changes can be used for Algorithmic Recourse (AR): they offer the group of principals a way to not only understand their agent’s behaviour, but also adjust or react to it.

The availability of open-source software to explain black-box models through counterfactuals is still limited. Most existing implementations are specific to particular methodologies. They are also exclusively built in Python and for Python models. The only existing unifying software approach, for example, is tailored to models built in the two most popular Python libraries for deep learning. The Julia ecosystem has so far lacked an open-source implementation of CE.

Through the work presented here, we aim to close that gap and thereby contribute to broader community efforts towards explainable AI. We envision this package to one day be the go-to place for Counterfactual Explanations in Julia. Thanks to Julia’s unique support for interoperability with foreign programming languages we believe that this library may ultimately also benefit the broader machine learning and data science community.

Our package provides a simple and intuitive interface to generate Counterfactual Explanations for differentiable classification models trained in Julia. It comes with detailed documentation involving various illustrative example datasets, linear and deep learning classifiers and counterfactual generators for binary and multi-class prediction tasks. A carefully designed package architecture allows for a seamless extension of the package functionality through custom generators and models. Through simple examples, we also demonstrate how to use our

package to explain models that were built and trained in `Python` and `R`, although at the time of writing this feature is still experimental.

The remainder of this article is structured as follows: Section ?? presents related work on explainable AI as well as a brief overview of the methodological framework underlying CE. Section ?? introduces the Julia package and its high-level architecture. Section ?? then presents a number of basic and advanced usage examples. In Section ?? we demonstrate how the package functionality can be customized and extended. To provide a flavour of its practical use, we use the package to explain models trained on MNIST data in Section ?. Finally, we also discuss the current limitations of our package, as well as its future outlook in Section ?. Section ? concludes.

Background and related work

In this section, we first briefly introduce the broad field of explainable artificial intelligence (XAI), before narrowing it down to Counterfactual Explanations. We introduce the methodological framework and finally point to existing open-source software.

Literature on explainable AI

The field of explainable AI is still relatively young and made up of a variety of subdomains, definitions, concepts and taxonomies. Covering all of these is beyond the scope of this article, so we will focus only on high-level concepts. The following literature surveys provide more detail: Arrieta et al. (2020) provide a broad overview of XAI [?]; Fan et al. (2020) focus on explainability in the context of deep learning [?]; and finally, Karimi et al. (2020) [?] and Verma et al. (2020) [?] offer detailed reviews of the literature on Counterfactual Explanations and Algorithmic Recourse.¹ Finally, Miller (2019) explicitly discusses the concept of explainability from the perspective of a social scientist [?].

The first broad distinction we want to make here is between **interpretable** and **explainable** AI. These terms are often used interchangeably, but this can lead to confusion. We find the distinction made in [?] useful: interpretable AI involves models that are inherently interpretable and transparent such as general additive models (GAM), decision trees and rule-based models; explainable AI may involve models that are not inherently interpretable but require additional tools to be explainable to humans. Examples of the latter include ensembles, support vector machines and deep neural networks. Some would argue that we best avoid the second category of models altogether and instead focus solely on interpretable AI [?]. While we agree that initial efforts should always be geared towards interpretable models, avoiding black boxes altogether would entail missed opportunities and anyway is probably not very realistic at this point. For that reason, we expect the need for explainable AI to persist in the near

¹Readers who prefer a text-book approach may also want to consider [?] and [?]

future. Explainable AI can further be broadly divided into **global** and **local** explainability: the former is concerned with explaining the average behaviour of a model, while the latter involves explanations for individual predictions [?]. Tools for global explainability include partial dependence plots (PDP), which involve the computation of marginal effects through Monte Carlo, and global surrogates. A surrogate model is an interpretable model that is trained to explain the predictions of a black-box model.

Counterfactual Explanations fall into the category of local methods: they explain how individual predictions change in response to individual feature perturbations. Among the most popular alternatives to Counterfactual Explanations are local surrogate explainers including local interpretable model-agnostic explanations (LIME) and Shapley additive explanations (SHAP). Since explanations produced by LIME and SHAP typically involve simple feature importance plots, they arguably rely on reasonably interpretable features at the very least. Contrary to Counterfactual Explanations, for example, it is not obvious how to apply LIME and SHAP to visual or audio data. Nonetheless, local surrogate explainers are among the most widely used XAI tools today, potentially because they are easily understood, relatively fast and implemented in popular programming languages. Proponents of surrogate explainers also commonly mention that there is a straightforward way to assess their reliability: a surrogate model that generates predictions in line with those produced by the black-box model is said to have high **fidelity** and therefore considered reliable. As intuitive as this notion may be, it also points to an obvious shortfall of surrogate explainers: even a high-fidelity surrogate model that produces the same predictions as the black-box model 99 per cent of the time is useless and potentially misleading for every 1 out of 100 individual predictions. A recent study has shown that even experienced data scientists tend to put too much trust in explanations produced by LIME and SHAP [?]. Another recent work has shown that both LIME and SHAP can be easily fooled: both methods depend on random input perturbations, a property that can be abused by adverse agents to essentially whitewash strongly biased black-box models [?]. In a related work the same authors find that while gradient-based Counterfactual Explanations can also be manipulated, there is a straightforward way to protect against this in practice [?]. In the context of quality assessment, it is also worth noting that - contrary to surrogate explainers - Counterfactual Explanations always achieve full fidelity by construction: counterfactuals are searched with respect to the black-box classifier, not some proxy for it. That being said, Counterfactual Explanations should also be used with care and research around them is still in its early stages. We shall discuss this in more detail in the following.

A framework for Counterfactual Explanations

Counterfactual search happens in the feature space²: we are interested in understanding how we need to change individual attributes in order to change the model output to a desired value or label [?]. Typically the underlying methodology is presented in the context of binary classification: $M : \mathcal{X} \mapsto \mathcal{Y}$ where $\mathcal{X} \subset \mathbb{R}^D$ and $\mathcal{Y} = \{0, 1\}$. Further, let $t = 1$ be the target

²Or, in the case of Latent Space generators, some latent representation of the feature space.

class and let x denote the factual feature vector of some individual sample outside of the target class, so $y = M(x) = 0$. We follow this convention here, though it should be noted that the ideas presented here also carry over to multi-class problems and regression [?].

The counterfactual search objective originally proposed by Wachter et al. (2017) [?] is as follows

$$\min_{x' \in \mathcal{X}} h(x') \quad \text{s. t.} \quad M(x') = t \quad (1)$$

where $h(\cdot)$ quantifies how complex or costly it is to go from the factual x to the counterfactual x' . To simplify things we can restate this constrained objective (Equation ??) as the following unconstrained and differentiable problem:

$$x' = \arg \min_{x'} \ell(M(x'), t) + \lambda h(x') \quad (2)$$

Here ℓ denotes some loss function targeting the deviation between the target label and the predicted label and λ governs the strength of the complexity penalty. Provided we have gradient access for the black-box model M the solution to this problem (Equation ??) can be found through gradient descent. This generic framework lays the foundation for most state-of-the-art approaches to counterfactual search and is also used as the baseline approach in our package. The hyperparameter λ is typically tuned through grid search or in some sense pre-determined by the nature of the problem. Conventional choices for ℓ include margin-based losses like cross-entropy loss and hinge loss. It is worth pointing out that the loss function is typically computed with respect to logits rather than predicted probabilities, a convention that we have chosen to follow.³

Numerous - and in some cases competing - extensions to this simple approach have been developed since Counterfactual Explanations were first proposed in 2017 (see [?] and [?] for surveys). The various approaches largely differ in how they define the complexity penalty. In the baseline paper [?], for example, $h(\cdot)$ is defined in terms of the Manhattan distance between factual and counterfactual feature values. While this is an intuitive choice, it is too simple to address many of the desirable properties of effective Counterfactual Explanations that have been set out. These desiderata include: **closeness** - the average distance between factual and counterfactual features should be small [?]; **actionability** - the proposed feature perturbation should actually be actionable ([?], [?]); **plausibility** - the counterfactual explanation should be realistic plausible to a human ([?], [?]); **unambiguity** - a human should have no trouble assigning a label to the counterfactual [?]; **sparsity** - the counterfactual explanation should involve as few individual feature changes as possible [?]; **robustness** - the counterfactual explanation should be robust to domain and model shifts [?]; **diversity** - ideally multiple

³While the rationale for this convention is not entirely obvious, implementations of loss functions with respect to logits are often numerically more stable. For example, the `logitbinarycrossentropy(y-hat, y)` implementation in `Flux.Losses` (used here) is more stable than the mathematically equivalent `binarycrossentropy(y-hat, y)`.

diverse Counterfactual Explanations should be provided [?]; and **causality** - Counterfactual Explanations should respect the structural causal model underlying the data generating process ([?],[?]).

Existing software

To the best of our knowledge, the package introduced here provides the first implementation of Counterfactual Explanations in Julia and therefore represents a novel contribution to the community. As for other programming languages, we are only aware of one other unifying framework: the recently introduced Python library **CARLA** [?]. In addition to that, there exists open-source code for some specific approaches to Counterfactual Explanations that have been proposed in recent years. The approach-specific implementations that we have been able to find are generally well-documented, but exclusively in Python. For example, a PyTorch implementation of a greedy generator for Bayesian models proposed in [?] has been released. As another example, the popular **InterpretML** library includes an implementation of a diverse counterfactual generator proposed by [?].

Generally speaking, software development in the space of XAI has largely focused on various global methods and surrogate explainers: implementations of PDP, LIME and SHAP are available for both Python (e.g. **lime**, **shap**) and R (e.g. **lime**, **iml**, **shapper**, **fastshap**). In the Julia space we have only been able to identify one package that falls into the broader scope of XAI, namely **ShapML.jl** which provides a fast implementation of SHAP.⁴ We also should not fail to mention the comprehensive **Interpretable AI** infrastructure, which focuses exclusively on interpretable models. Arguably the current availability of tools for explaining black-box models in Julia is limited, but it appears that the community is invested in changing that. The team behind **MLJ.jl**, for example, has contributed contributors for a project about both interpretable and explainable AI in 2022.⁵ With our work on Counterfactual Explanations we hope to contribute to these efforts. We think that because of its unique transparency the Julia language naturally lends itself towards building a greater degree of trust in machine learning and artificial intelligence.

Introducing: CounterfactualExplanations.jl

Figure ?? provides an overview of the package architecture. It is built around two core modules that are designed to be as extensible as possible through dispatch: 1) **Models** is concerned with making any arbitrary model compatible with the package; 2) **Generators** is used to

⁴See here: <https://github.com/nredell/ShapML.jl>

⁵For details, see the Google Summer of Code 2022 project proposal: https://julialang.org/jsoc/gsoc/MLJ/#interpretable_machine_learning_in_julia.

implement arbitrary counterfactual search algorithms.⁶ The core function of the package `generate_counterfactual` uses an instance of type `T <: AbstractFittedModel` produced by the `Models` module and an instance of type `T <: AbstractGenerator` produced by the `Generators` module. Relating this to the methodology outlined in Section ??, the former instance corresponds to the model M , while the latter defines the rules for the counterfactual search (Equation ??). At the time of writing the following counterfactual generators have been implemented in the package:

- Generic [?]
- Greedy [?]
- DiCE [?]
- Latent Space Search as in REVISE [?] and CLUE [?]
- ClaPROAR [?]
- Gravitational [?]

The package currently offers native support for deep learning models built in [Flux](#).

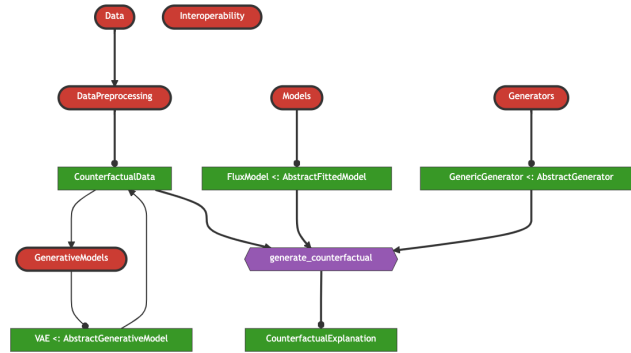


Figure 1: High-level schematic overview of package architecture. Modules are shown in red, structs in green and functions in blue.

Basic Usage

In the following, we begin our exploration of the package functionality with a simple example. We then turn to a more advanced usage example and show how users can impose mutability constraints on features.

⁶We have made an effort to keep the code base as flexible and extensible as possible, but cannot guarantee at this point that any counterfactual generator can be implemented without further adaptation.

A Simple Generic Generator

Listing ?? below provides a complete example demonstrating how the framework presented in Section ?? can be implemented in Julia with our package. Using a synthetic data set with linearly separable samples we first define our model and then generate a counterfactual for a randomly selected sample. Figure ?? shows the resulting counterfactual path in the two-dimensional feature space. Features go through iterative perturbations until the desired confidence level is reached as illustrated by the contour in the background, which indicates the classifier’s predicted probability that the label is equal to 1.

It may help to go through the relevant parts of the code in some more detail starting from the part involving the model. For illustrative purposes the `Models` module ships with a constructor for a logistic regression model: `LogisticModel(W::Matrix,b::AbstractArray) <: AbstractFittedModel`. This constructor does not fit the regression model but rather takes its underlying parameters as given. In other words, it is generally assumed that the user has already estimated a model. Based on the provided estimates two functions are already implemented that compute logits and probabilities for the model, respectively. Below we will see how users can use dispatch to extend these functions for use with arbitrary models. For now, it is enough to note that those methods define how the model makes its predictions $M(x)$ and hence they form an integral part of the counterfactual search. With the model M defined in the code below we go on to set up the counterfactual search as follows: 1) specify the other class as our `target` label ($t = 1$) in line ??; 2) choose a random sample x from the non-target class in line ??; 3) define the counterfactual generator in line ??; and finally run the counterfactual search in line ??. Generators like the `GenericGenerator` take several optional arguments that govern the strength of the complexity penalty, the step size for gradient descent and the tolerance for convergence among other things. This will be discussed in some more detail when looking at the advanced usage example below.

[language=Julia, escapechar=@, numbers=left, label=lst:simple, caption=] Data and Classifier:
`counterfactual_data = load_linearly_separable() M = fit_model(counterfactual_data, : Linear)`

Factual and Target: `yhat = predict_label(M, counterfactual_data) target = 2targetlabel @@ candidates = findall(vec(yhat).! = target) chosen = rand(candidates) x = select_factual(counterfactual_data, chosen) @@`

Counterfactual search: `generator = GenericGenerator() @@ counterfactual = generate_counterfactual(x, target, co`

In this simple example, the generic generator produces an effective counterfactual: the decision boundary is crossed (i.e. the counterfactual explanation is valid) and upon visual inspection, the counterfactual seems plausible (Figure ??). Still, the example also illustrates that things may well go wrong. Since the underlying model produces high-confidence predictions in regions free of any data - that is regions with high epistemic uncertainty - it is easy to think of scenarios that involve valid but unrealistic counterfactuals. Similarly, any degree of overfitting can be expected to result in more ambiguous Counterfactual Explanations, since it reduces the classifier’s sensitivity to regions with high aleatoric uncertainty. Consider, for example, the scenario illustrated in Figure ??, which involves the same logistic classifier, but a massively

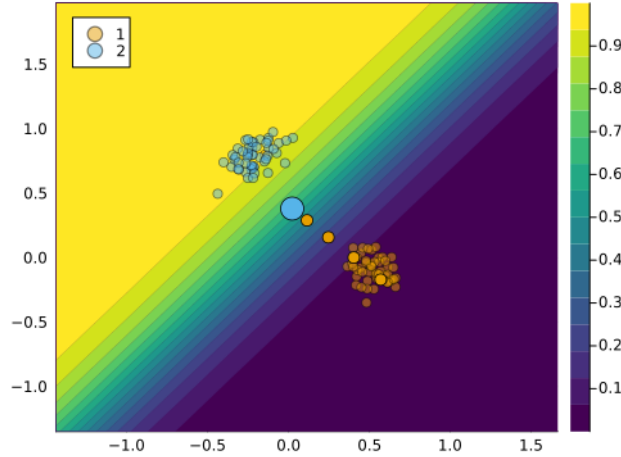


Figure 2: Counterfactual path using generic counterfactual generator for conventional binary classifier.

overfitted version of it. In this case, generic search may yield an unrealistic counterfactual that is well into the yellow region and yet far away from all other samples (red marker) or an ambiguous counterfactual near the decision boundary (purple marker).

More Advanced Generators

The more advanced generators currently implemented in `CounterfactualExplanations.jl` are designed to generate more realistic counterfactuals. In this context, ‘realistic’ is defined in the sense that counterfactuals ought to be generated by the same data-generating process (DGP) that generates the actual data points. To this end, **Latent Space** generators like REVISE [?] use a separate generative model to learn the DGP. We refer to them as Latent Space generators, because they search counterfactuals in the latent embedding learned by the generative model.⁷ The **Greedy** approach [?] instead relies on minimizing predictive uncertainty in order to generate realistic counterfactuals. **CLUE** [?] can be thought of as a combination of these two ideas. The other generator currently implemented, **DiCE** [?], generates multiple counterfactuals at once that are as diverse as possible. This strategy is based on the intuition that a wide variety of diverse explanations may be suitable depending on the practical context.

Listing ?? below shows a more advanced usage example involving the DiCE generator. Once again it is worth dwelling on this for a moment. In line ?? we instantiate a Flux optimizer that will determine how exactly the counterfactual search objective is optimized. That optimizer is

⁷Currently our implementation relies on a Variational Autoencoder (VAE)

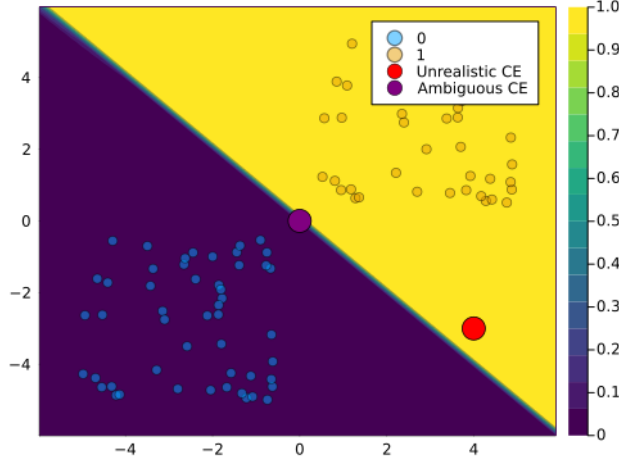


Figure 3: Unrealistic and ambiguous counterfactuals that may be produced by generic counterfactual search for an overfitted conventional binary classifier.

then fed to the `DiCEGenerator` in line ??⁸. The main API call to generate counterfactuals is the same as before, but note that in line ?? we have specified an optional key argument that determines how many counterfactuals are generated. For the DiCE generator it naturally makes sense to generate multiple counterfactuals, but note that this is in principle also possible for all other generators.⁹ Figure ?? shows the resulting output. It was generated by calling the generic `plot` method directly on the object returned by `generate_counterfactual`.

```
[language=Julia, escapechar=@, numbers=left, label=lst:binary-advanced, caption=] Counter-
factual search: opt = Flux.Optimise.Descent(1.0) @@ generator = DiCEGenerator(;opt = opt)
@@ counterfactuals = generate_counterfactual(x, target, counterfactual_data, M, generator; num_counterfactuals=
5@@)Plottingplt = plot(counterfactuals)
```

Mutability Constraints

In practice, features usually cannot be perturbed arbitrarily. Suppose, for example, that one of the features used by a bank to predict the creditworthiness of its clients is *gender*. If a counterfactual explanation for the prediction model indicates that female clients should change their gender to improve their creditworthiness, then this is an interesting insight (it reveals gender bias), but it is not usually an actionable transformation in practice. In such cases, we may want to constrain the mutability of features to ensure actionable and realistic recourse.

⁸Note that all differentiable generators except the `GreedyGenerator` work with Flux optimizers and accept them as an optional key argument.

⁹By default counterfactuals are initialized by adding a small, random perturbation, as this improves adversarial robustness [?]. Therefore, generating multiple counterfactuals will yield multiple distinct outcomes even without an explicit diversity constraint.

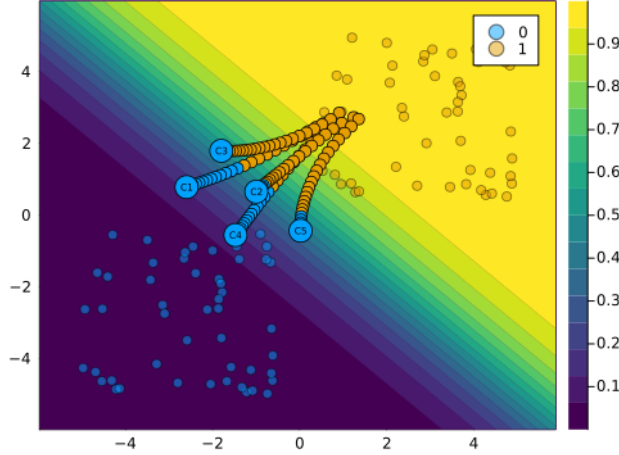


Figure 4: Counterfactual path using the DiCE generator.

To illustrate how this can be implemented in `CounterfactualExplanations.jl` we will look at the linearly separable toy dataset again.

Mutability of features can be defined in terms of four different options: 1) the feature is mutable in both directions, 2) the feature can only increase (e.g. *age*), 3) the feature can only decrease (e.g. *time left* until your next deadline) and 4) the feature is not mutable (e.g. *skin colour*, *ethnicity*, ...). To specify which category a feature belongs to, users can pass a vector of symbols containing the mutability constraints at the pre-processing stage. For each feature one can choose from these four options: `:both` (mutable in both directions), `:increase` (only up), `:decrease` (only down) and `:none` (immutable). By default, `nothing` is passed to that keyword argument and it is assumed that all features are mutable in both directions.¹⁰

Below we impose that the second feature is immutable.

```
[language=Julia, escapechar=@, numbers=left, label=lst:mutability, caption=] counterfactual_data =
CounterfactualData(X, ys'; mutability = [: both, : none])
```

The resulting counterfactual path is shown in Figure ?? below. Since only the first feature can be perturbed, the sample can only move along the horizontal axis.

Customization and Extensibility

One of our priorities has been to make `CounterfactualExplanations` customizable and extensible. In the long term, we aim to add support for more default models and counterfactual

¹⁰Mutability constraints are currently not yet implemented for Latent Space generators.

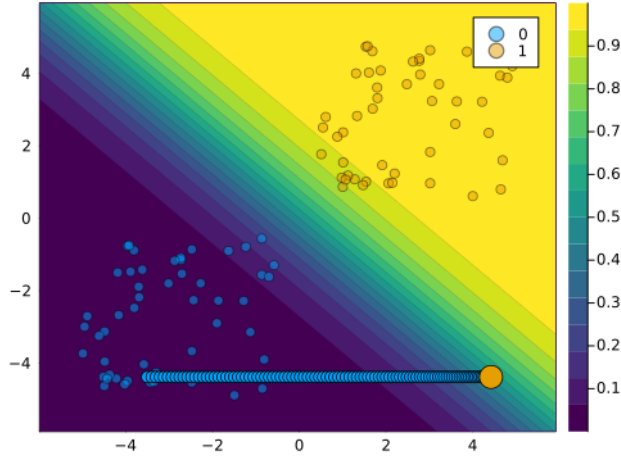


Figure 5: Counterfactual path with immutable feature.

generators. In the short term, it is designed to allow users to integrate models and generators themselves. Ideally, these community efforts will facilitate our long-term goals.

Adding Custom Models

At the high level, only two steps are necessary to make any supervised learning model compatible with our package:

Subtyping: the model needs to be declared as a subtype of `AbstractFittedModel`.

Dispatch: the functions `logits` and `probs` need to be extended through custom methods for the model in question.

To demonstrate how this can be done in practice, we will reiterate here how native support for `Flux.jl` ([?]) deep learning models was enabled.¹¹ Once again we use synthetic data for an illustrative example. Listing ?? below builds a simple model architecture that can be used for a multi-class prediction task. Note how outputs from the final layer are not passed through a softmax activation function, since the counterfactual loss is evaluated with respect to logits as we discussed earlier. The model is trained with dropout for ten training epochs.

```
[language=Julia, escapechar=@, numbers=left, label=lst:nn, caption=] n_hidden =
32output_dim = length(unique(y))input_dim = 2model = Chain(Dense(input_dim, n_hidden, activation), Dropout
```

Listing ?? below implements the two steps that were necessary to make Flux models compatible with the package. In line ?? we declare our new struct as a subtype of

¹¹Flux models are now natively supported by our package and can be instantiated by calling `FluxModel()`.

`AbstractDifferentiableModel`, which itself is an abstract subtype of `AbstractFittedModel`.¹² Computing logits amounts to just calling the model on inputs. Predicted probabilities for labels can then be computed by passing predicted logits through the softmax function.

```
[language=Julia, escapechar=@, numbers=left, label=lst:mymodel, caption=] Step 1) struct
MyFluxModel <: AbstractDifferentiableModel @@ model::Any likelihood::Symbol @@ end
```

```
Step 2) import functions in order to extend import CounterfactualExplanations.Models: logits
import CounterfactualExplanations.Models: probs logits(M::MyFluxModel, X::AbstractArray)
= M.model(X) probs(M::MyFluxModel, X::AbstractArray) = softmax(logits(M, X)) M =
MyFluxModel(model)
```

The API call for actually generating counterfactuals for our new model is the same as before. Figure ?? shows the resulting counterfactual path for a randomly chosen sample. In this case, the contour shows the predicted probability that the input is in the target class ($t = 2$). Generic search yields a valid, realistic and largely unambiguous counterfactual.

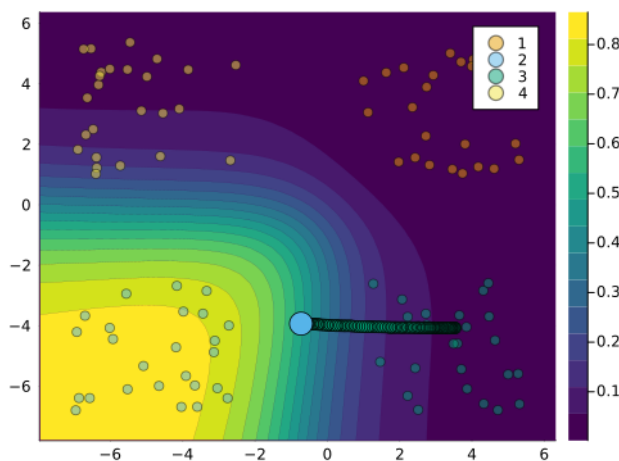


Figure 6: Counterfactual path using generic counterfactual generator for multi-class classifier.

Adding Custom Generators

To illustrate how custom generators can be implemented we will consider a simple example of a generator that extends the functionality of our `GenericGenerator`. We have noted elsewhere that the effectiveness of Counterfactual Explanations depends to some degree on the quality of the fitted model. Another, perhaps trivial, thing to note is that Counterfactual Explanations are not unique: there are potentially many valid counterfactual paths. One idea building on

¹²Note that in line ?? we also provide a field determining the likelihood. This is optional and only used internally to determine which loss function to use in the counterfactual search. If this field is not provided to the model, the loss function needs to be explicitly supplied to the generator.

these two observations might be to introduce some form of regularization in the counterfactual search. For example, we could use dropout to randomly switch features on and off in each iteration. Without dwelling further on the merit of this idea, we will now briefly show how this can be implemented.

A Generator with Dropout

Listing ?? below implements two important steps: 1) create an abstract subtype of the `AbstractGradientBasedGenerator` and 2) create a constructor similar to the `GenericConstructor`, but with one additional field for the probability of dropout.

```
[language=Julia, escapechar=@, numbers=left, label=lst:dropout, caption=] Abstract suptype:
abstract type AbstractDropoutGenerator <: AbstractGradientBasedGenerator end
```

```
Constructor: struct DropoutGenerator <: AbstractDropoutGenerator loss::Symbol loss
function complexity::Function complexity function @λ@::AbstractFloat strength of penalty
decisionthreshold :: Union{Nothing, AbstractFloat} opt :: Anyoptimizer@τ@::AbstractFloat
tolerance for convergence p_dropout :: AbstractFloat dropoutrateend
```

Next, in listing ?? we define how feature perturbations are generated for our custom dropout generator: in particular, we extend the relevant function through a method that implements the dropout logic.

```
[language=Julia, escapechar=@, numbers=left, label=lst:generate, caption=] using Counterfac-
tualExplanations.Generators import Generators: generate_perturbationsimport Generators :
propose_stateusing StatsBasefunction generate_perturbations(generator :: AbstractDropoutGenerator, counter-
factual_state)@s'@ = deepcopy(counterfactual_state.@s'@) new@s'@ = propose_state(generator, counterfactual_state)@Δs
= new@s'@ - @s'@ gradient step
```

```
Dropout: set_t_o_z_ero = sample(1 : length(@Δs'@), Int(round(generator.p_dropout *
length(@Δs'@))), replace=false ) @Δs'@[set_t_o_z_ero]. = 0return @Δs'@ end
```

Finally, we proceed to generate counterfactuals in the same way we always do. The resulting counterfactual path is shown in Figure ??.

A Real-World Example — MNIST

Now that we have explained the basic functionality of `CounterfactualExplanations.jl` through some synthetic examples, it is time to work through an example involving real data. The MNIST dataset contains 60,000 training samples of handwritten digits in the form of 28x28 pixel grey-scale images [?]. Each image is associated with a label indicating the digit (0-9) that the image represents. The data makes for an interesting case study of Counterfactual Explanations, because humans have a good idea of what realistic counterfactuals of digits look like. For example, if you were asked to pick up an eraser and turn the digit in Figure ?? into

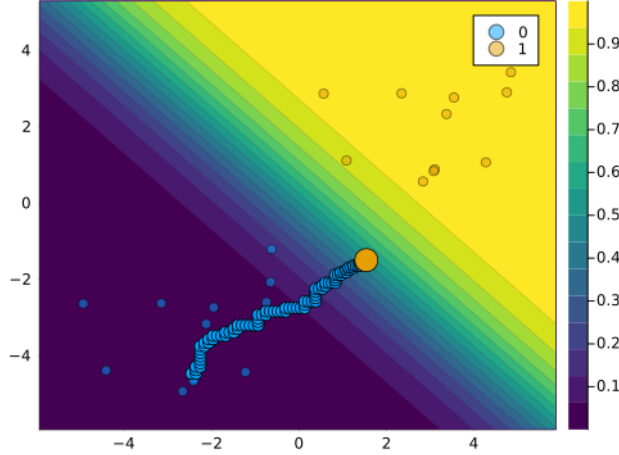


Figure 7: Counterfactual path for a generator with dropout.

a four (4) you would know exactly what to do: just erase the top part. Schut et al. (2021) [?] leverage this idea to illustrate to the reader that their methodology produces realistic counterfactuals. In what follows we replicate some of their findings. You as the reader are therefore the perfect judge to evaluate the quality of the Counterfactual Explanations presented here.

On the model side, we will use two pre-trained classifiers¹³: firstly, a simple multi-layer perceptron (MLP) and, secondly, a deep ensemble composed of five such MLPs following [?]. Deep ensembles are approximate Bayesian model averages that have been shown to yield high-quality estimates of predictive uncertainty for neural networks ([?], [?]). Our package has native support for ensembles of Flux models. Listing ?? loads and prepares the pretrained models:

```
[language=Julia, escapechar=@, numbers=left, label=lst:mnist-setup, caption=] using
Flux X, ys = mnist_data() counterfactual_data = CounterfactualData(X,ys) model =
mnist_model() ensemble = mnist_ensemble() M = FluxModel(model) M_ensemble =
FluxEnsemble(ensemble)
```

For the counterfactual search, we will use four different combinations of classifiers and generators: firstly, the generic approach for the MLP; secondly, the greedy approach for the MLP; thirdly, the generic approach for the deep ensemble; and finally, the greedy approach for the deep ensemble.

We begin by turning the nine in Figure ?? into a four. Figure ?? shows the resulting counterfactuals. In every case, the desired label switch is achieved, but arguably from a human perspective, only the counterfactuals for the deep ensemble look like a four. The generic generator produces mild perturbations in regions that seem irrelevant from a human perspective,

¹³The pre-trained models were stored as package artifacts and loaded through helper functions.

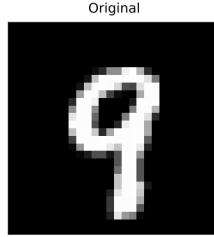


Figure 8: A handwritten nine (9) randomly drawn from the MNIST dataset.

but still yields a counterfactual that can pass as a four. The greedy approach [?] targets pixels at the top of the handwritten nine and yields the best result overall. For the non-bayesian MLP, both the generic and the greedy approaches generate counterfactuals that look much like adversarial examples: they perturb pixels in seemingly random regions on the image. Figure ?? shows another example. This time the goal is to turn a randomly chosen three (3) into an eight (8). Once again the outcomes for the deep ensemble look more realistic, but overall the generated counterfactuals look less effective than those in Figure ?. The results could likely be improved by using adversarial training for the classifiers as recommended in [?].

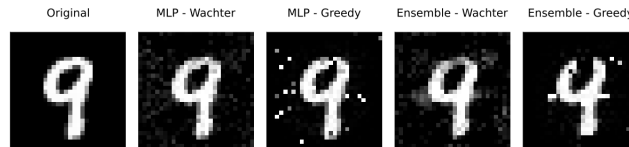


Figure 9: Counterfactual explanations for MNIST: turning a nine (9) into a four (4).

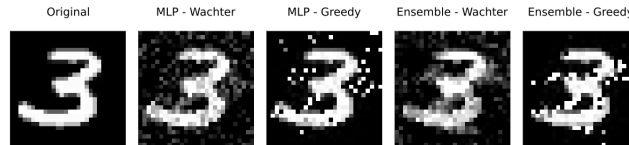


Figure 10: Counterfactual explanations for MNIST: turning a three (3) into an eight (8).

Overall, the examples in this section demonstrate two points that we have already made earlier: firstly, the findings in [?] can complement other existing approaches to counterfactual generation; and secondly, the quality of the classifier is typically reflected in the quality of the Counterfactual Explanations. In other words, we cannot easily generate effective Counterfactual Explanations for a poorly trained model.

A notable exception to this is Latent Space generators. The counterfactual in Figure ?? was generated using the REVISE generator introduced earlier. The underlying black-box model is the same as before and yet the quality of the produced counterfactual is arguably the most compelling out of all examples shown here. While in terms of meeting the desiderata for

realistic counterfactuals, REVISE does remarkably well here, one has to wonder how desirable it is to generate compelling explanations for inherently unstable models. Applying REVISE blindly to this particular problem may lead users to believe that the classifier is well-specified: after all, the explanation looks plausible from a human perspective. The fact that less plausible counterfactuals also yield a change in the predicted outcome goes unnoticed.

It may therefore actually be desirable that the quality of counterfactuals is inherently linked to the quality of the black-box model: if a model bases its predictions on representations that are not intuitive to a human, we would like that to be evident from the counterfactual explanation. From that perspective, Counterfactual Explanations can help us not only understand a black-box model but potentially also guide us in improving it.

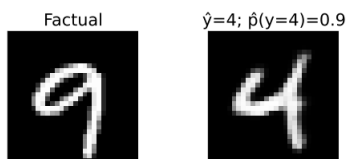


Figure 11: Counterfactual explanations for MNIST using a Latent Space generator with a well-specified generative model.

Discussion and Outlook

We believe that this package in its current form offers a valuable contribution to ongoing efforts towards explainable artificial intelligence by the broader Julia community. That being said, there is significant scope for exciting future developments, which we briefly outline in this final section.

Candidate models and generators

At the time of writing the package supports a handful of default models and generators either natively or through minimal augmentation. In future work, we would like to prioritize the addition of further predictive models and especially generators. Concerning the former, it would be useful to add native support for any arbitrary Flux model, as well as predictive models built in other popular libraries: in particular `MLJ.jl`, but also `ScikitLearn.jl`, `GLM.jl` and `Turing.jl`. This may also involve adding support for regression models as well as non-differentiable models. In terms of counterfactual generators, we are particularly interested in having the following approaches added in the near future: MINT [?] and ROAR [?]. Through its composable nature, our package may also allow for combining different approaches.

Additional datasets

For benchmarking and testing purposes it will be crucial to add more datasets to our library. We would like to prioritize datasets that have typically been used in the literature on counterfactual explanations including Adult, COMPAS and German Credit [?]. That being said, there is also scope for adding data sources that have so far not been explored much in this context including image, audio, natural language and time-series data.

Adding Foreign Language Support

The Julia language offers unique support for programming language interoperability. For example, calling R or Python is made remarkably easy through auxiliary packages like `RCall.jl`, `PythonCall.jl` and `PyCall.jl`, respectively. Early experimentation has shown that this functionality can be leveraged to make `CounterfactualExplanations.jl` compatible with models that were developed in foreign programming languages. At the time of writing this feature is still not mature enough, but we hope to add native support for explaining [torch](#) models trained in R or Python in the near future.¹⁴

Concluding remarks

The goal of this paper was to illustrate the need for explainability in machine learning and the promise of Counterfactual Explanations in this context. To this end, we introduced `CounterfactualExplanation.jl`: a package for generating Counterfactual Explanations and Algorithmic Recourse in Julia. Through various synthetic and real-world examples, we have demonstrated the basic usage of the package and shown how it can be easily customized and extended. We envision this package to one day constitute the go-to place for explaining arbitrary predictive models through a diverse suite of counterfactual generators. As a major next step, we would therefore like to interface our library with the popular [MLJ.jl](#) package for machine learning in Julia. The package can also serve as a testing ground for new and existing methodological approaches to Counterfactual Explanations and Algorithmic Recourse. We invite the Julia community to contribute to these goals through usage, open challenge and active development.

Acknowledgements

Patrick is grateful to his PhD supervisors and co-authors, Cynthia C. S. Liem and Arie van Deursen, for being so supportive of his work on open-source developments. The authors are

¹⁴Early experiments with this feature can be found here: <https://www.palmtmeyer.com/CounterfactualExplanations.jl/dev/tutorials/interop/>

grateful to the Julia community for being welcoming and open and for supporting research contributions like this one.