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► To cite this version:

Juan F P J Abascal, Thomas Baudier, Romain Phan, Audrey Repetti, Nicolas Ducros. SPyRiT: an open source package for single-pixel imaging based on deep learning. 2024. hal-04662876v2

HAL Id: hal-04662876

<https://hal.science/hal-04662876v2>

Preprint submitted on 11 Sep 2024 (v2), last revised 16 Oct 2024 (v3)

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SPyRiT: an open source package for single-pixel imaging based on deep learning

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Abstract: Single-pixel imaging is able to acquire an image from a few point measurements thanks to dedicated reconstruction algorithms. In recent years, reconstruction approaches based on deep learning have outperformed most alternatives. However, computational experiments and data-driven methods have become difficult, if not impossible, to reproduce. The development of tools enabling reproducibility and benchmarking is therefore now essential. This paper describes SPyRiT, an open source PyTorch-based toolbox capable of handling various simulation configurations and reconstruction methods based on deep learning. In particular, we compare several supervised and plug-and-play methods, including post-processing and iterative strategies. Our results demonstrate that supervised methods trained on simulated data can be successfully applied to experimental data when the signal-to-noise ratio of the measurements is higher or equal to that of the training phase. On the other hand, the hyperparameter of the plug-and-play methods can be tuned to manage lower signal-to-noise ratios. The modularity of SPyRiT enables the evaluation of various configurations and the rigorous benchmarking of reconstructions based on deep learning in single-pixel imaging, as well as in related fields such as ghost imaging.

1. Introduction

Single-pixel imaging is a technique that enables an image to be acquired from a set of point measurements using dedicated reconstruction algorithms [1, 2]. The technique can be traced back to the concept of Hadamard spectroscopy [3], that introduced Hadamard-modulated measurements to enhance the signal-to-noise ratio (SNR) of images reconstructed using the least squares method. Single-pixel imaging has gained renewed interest with the advent of compressed sensing theory, providing a theoretical framework to ensure perfect reconstruction of an image acquired from few measurements obtained with random modulations [4]. The many different applications of the technique include imaging in the visible and infrared domains [5], in addition to the mid-infrared [6], ultraviolet [7], terahertz [8] and X-ray [9] ranges, as well as through scattering media [10], fluorescence lifetime imaging [11], 3D time-of-flight imaging [12], time-of-flight LiDAR [13] and light-field microscopy [14].

Deep learning has revolutionized the field of image reconstruction [15] and greatly advanced computational optics [16]. Since the first application of deep learning to single-pixel imaging [17], a great variety of data-driven reconstruction methods have been designed for the field. Supervised methods train the free parameters of a reconstruction algorithm from image-measurement pairs. Simple yet efficient reconstruction algorithms are obtained by post-processing a first (e.g., linear) reconstruction by an image-domain neural network (e.g., a U-Net [18] or an attention network [19]). The first reconstruction step can be learned from the data in an end-to-end [17] or two-step [20] manner, chosen as the pseudo-inverse solution [21, 22], or the minimum mean squares error solution [23]. Following the trend of algorithm unrolling [24, 25], an empirical expectation maximisation network was designed in [26] while [27] considered unrolling the iterative hard thresholding for expanders. Adversarial training has also been considered [28, 29].

47 To improve the generalization ability of supervised methods, one strategy involves fine-tuning
 48 using a physics-based loss [30]. An alternative is to consider plug-and-play (PnP) methods
 49 that combine a (deep) denoiser prior with a model-based reconstruction algorithm. Multiple
 50 configurations (e.g., sampling ratio, noise level, type of modulation) can, therefore, be considered
 51 using the same denoiser, whereas supervised methods require retraining. Among the possible
 52 model-based reconstruction algorithms that can be used for PnP, the proximal gradient descent [31]
 53 or the alternating direction method of multipliers algorithm [32] have been widely used in imaging.
 54 Different types of denoisers can be considered, such as traditional (e.g., BM3D [33]) or U-Net
 55 based denoisers (e.g., U-Net [18], DR-UNet [34]), or auto-regressive models [35]. More recently,
 56 untrained networks have emerged that do not require pretraining [36, 37].

57 In this new data-driven deep learning era, reproducibility is a major challenge. Indeed, despite
 58 huge progress in both the practical and theoretical aspects, most computational experiments and
 59 data-driven methods have become difficult, if not impossible, to reproduce by an independent
 60 researcher [38], an issue referred to as the *reproducibility crisis*. Open source platforms with
 61 reference datasets and reconstruction algorithms are therefore required in order to ensure the
 62 reproducibility of results and fair benchmarking needed to establish reliable conclusions.

63 This work introduces SPyRiT, the first, to the best of our knowledge, package dedicated to
 64 single-pixel imaging reconstruction based on deep learning. Though packages for solving general
 65 inverse problems using deep learning are available (e.g., Pixu [39] or DeepInv [40]), dedicated
 66 packages are usually preferred when targeting specific applications (e.g., RTK [41], ASTRA [42]
 67 or TIGRE [43] in computed tomography; BART [44] in magnetic resonance imaging). SPyRiT,
 68 on the other hand, provides a platform for the simulation and reconstruction of single-pixel
 69 measurements, integrated within the OpenSpyrit ecosystem that provides data and hardware
 70 control software [45]. The modular structure of the Python-based package allows users to
 71 simulate measurements from images, simulate corrupted noisy measurements, process noisy
 72 measurements prior to reconstruction, define data-driven reconstruction algorithms and train the
 73 associated networks.

74 To illustrate the capabilities of SPyRiT, we implement and compare six different data-driven
 75 reconstruction methods, belonging to the supervised and PnP families of algorithms. All methods
 76 are assessed in a controlled manner by evaluation of the images reconstructed by SPyRiT from
 77 the ImageNet dataset and SPIHIM experimental dataset. While SPyRiT has been designed for
 78 single-pixel imaging, it may also benefit other computational optical imaging modalities, e.g.,
 79 ghost imaging which is based on the same imaging principle.

80 2. Theory

81 2.1. Single-pixel imaging forward model

82 Single-pixel imaging aims to recover an unknown image $x \in \mathbb{R}^N$ from a few noisy observations

$$m \approx Hx, \quad (1)$$

83 where $H: \mathbb{R}^N \rightarrow \mathbb{R}^M$ is a linear measurement operator. In the case when $M = N$, it may be
 84 desirable to work with orthogonal bases, such as Hadamard or Fourier [46, 47] to benefit from
 85 Fellgett’s advantage for improved SNR [3]. This implies patterns with negative values¹. In
 86 practice, however, measurements are obtained by uploading a set of light patterns onto a spatial
 87 light modulator (e.g., a digital micromirror device (DMD), see Fig. 1). Therefore, only positive
 88 patterns can be implemented. We model the actual acquisition process as

$$y = \mathcal{N}(Ax), \quad (2)$$

¹An orthogonal matrix with non-negative entries is a permutation matrix, i.e., a matrix that has only one non zero entry (equal to one) in each row. This case corresponds to measuring each pixel in the scene independently

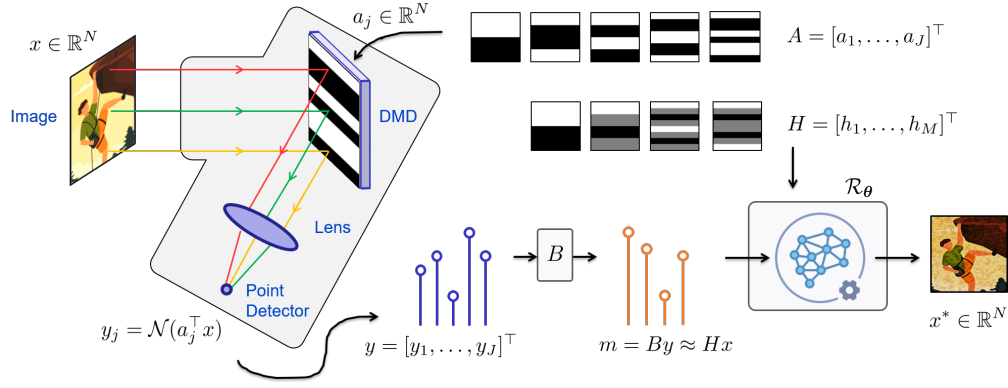


Fig. 1. Principle of single-pixel imaging. A single-pixel camera measures a noisy version of the scalar product of some image $x \in \mathbb{R}^N$ and a DMD pattern $a_j \in \mathbb{R}^N$. The measurement vector $y \in \mathbb{R}^J$, that collects all measurements obtained for all DMD patterns, may be preprocessed, leading to the preprocessed measurement vector $m \in \mathbb{R}^M$. A reconstruction algorithm \mathcal{R}_θ is necessary to estimate the unknown image x from the preprocessed measurements.

89 where $\mathcal{N}: \mathbb{R}^J \rightarrow \mathbb{R}^J$ represents a (not necessarily linear) noise operator (e.g., Poisson or
 90 Poisson-Gaussian), $A: \mathbb{R}^N \rightarrow \mathbb{R}^J$ is the actual acquisition operator that models the (positive)
 91 DMD patterns, and J is the number of DMD patterns.

92 2.2. Handling non negativity with preprocessing

93 We may consider preprocessing techniques that transform the actual model Eq. (2) into the target
 94 model Eq. (1)

$$m = By \approx Hx, \quad (3)$$

95 where $B: \mathbb{R}^J \rightarrow \mathbb{R}^M$ is the (linear) preprocessing operator chosen such that $BA = H$. Note
 96 that the noise of the preprocessed measurements $m = By$ is not the same as that of the actual
 97 measurements y .

98 In the simple case when H has only non-negative entries, we can choose $A = H$ and B is
 99 the identity matrix. There exist multiple variants to build the preprocessing operator such that
 100 $BA = H$ when H has negative entries (e.g., see [48]). A simple workaround consists in splitting
 101 the positive and negative entries of the matrix. Alternatively, one can add an appropriate constant
 102 to the patterns, which usually leads to increased noise.

103 2.3. Data-driven reconstruction

104 In the presence of noise and when fewer measurements than unknowns are available (i.e., $M < N$),
 105 regularized approaches must be adopted (see Appendix 5). Data-driven methods based on deep
 106 learning are a modern regularized approach. They aim to find an estimate $x^* \in \mathbb{R}^N$ of the
 107 unknown image x from the preprocessed measurements By (see Eq. (3)), using a reconstruction
 108 operator $\mathcal{R}_{\theta^*}: \mathbb{R}^M \rightarrow \mathbb{R}^N$. Specifically,

$$\mathcal{R}_{\theta^*}(m) = x^* \approx x, \quad (4)$$

109 where θ^* represents the parameters learned during a training procedure.

110 In the case of supervised learning, it is assumed that a training dataset $\{x_i, y_i\}_{1 \leq i \leq I}$ of pairs of
 111 ground truth images and measurements is available. θ^* is then obtained by solving

$$\text{minimize}_{\theta} \sum_{i=1}^I \mathcal{L}(x_i, \mathcal{R}_{\theta}(y_i)), \quad (5)$$

112 where \mathcal{L} is the training loss (e.g., squared error). It should be noted that if only a dataset of
 113 ground truth images $\{x_i\}_{1 \leq i \leq I}$ is available, the associated set of measurements can be obtained
 114 by defining $y_i = \mathcal{N}(Ax_i)$, $1 \leq i \leq I$.

115 The design of the reconstruction operator \mathcal{R}_{θ} has been the topic of extensive research over
 116 the last decade. A simple yet efficient method consists in correcting a traditional (e.g. linear)
 117 reconstruction by a data-driven nonlinear step [49]. In this context,

$$\mathcal{R}_{\theta} = \mathcal{G}_{\theta} \circ \mathcal{R}, \quad (6)$$

118 where $\mathcal{R}: \mathbb{R}^M \rightarrow \mathbb{R}^N$ is a traditional hand-crafted (e.g., regularized) reconstruction operator
 119 and $\mathcal{G}_{\theta}: \mathbb{R}^N \rightarrow \mathbb{R}^N$ is a nonlinear neural network that acts in the image domain. Algorithm
 120 unfolding can be seen as a generalization of Eq. (6), which consists in defining \mathcal{R}_{θ} from an
 121 iterative scheme

$$\mathcal{R}_{\theta} = \mathcal{R}_{\theta_K} \circ \dots \circ \mathcal{R}_{\theta_1}, \quad (7)$$

122 where \mathcal{R}_{θ_k} can be interpreted as the computation of the k -th iteration of the iterative scheme
 123 and $\theta = \bigcup_k \theta_k$. Many variants of unfolded algorithms have been proposed in the literature [25].
 124 The choice of \mathcal{R}_{θ_k} depends on the choice of the algorithm that is unrolled. It generally involves
 125 one or several analytical steps that rely on A or H , their adjoint operators (or pseudo-inverse)
 126 as well as one or several neural networks. Some standard architectures for \mathcal{R}_{θ_k} are described
 127 in Section 2.4. In particular, the formulation of Eq. (7) encompasses PnP and regularization
 128 by denoising methods, for which the neural networks/denoisers involved in \mathcal{R}_{θ_k} are trained
 129 beforehand, independently of A or H .

130 2.4. Standard data-driven architectures

131 A simple choice for the first step of the post-processing approach defined by Eq. (6) is to use the
 132 pseudo-inverse of H , i.e.,

$$\mathcal{R}(m) = H^{\dagger} m. \quad (8)$$

133 An alternative is to use the minimum mean square estimator [50], i.e.,

$$\mathcal{R}(m) = \Sigma H^{\top} (H \Sigma H^{\top} + \Gamma)^{-1} m, \quad (9)$$

134 where $\Sigma \in \mathbb{R}^{N \times N}$ represents the image covariance and $\Gamma \in \mathbb{R}^{M \times M}$ the noise covariance. These
 135 two methods are further detailed in Appendix A and Appendix A.2.

136 A simple choice for the iterative method described in Eq. (7) is the proximal gradient
 137 descent [51] for solving the regularized least-squares problem (see Appendix A),

$$x_{k+1} = \mathcal{R}_{\theta_k}(x_k) = \mathcal{G}_{\theta_k}(x_k - \gamma_k H^{\top} (H x_k - m)), \quad (10)$$

138 where the proximal denoiser has been replaced by a neural network $\mathcal{G}_{\theta_k}: \mathbb{R}^N \rightarrow \mathbb{R}^N$ acting in
 139 the image domain and $\gamma_k > 0$ is the step size.

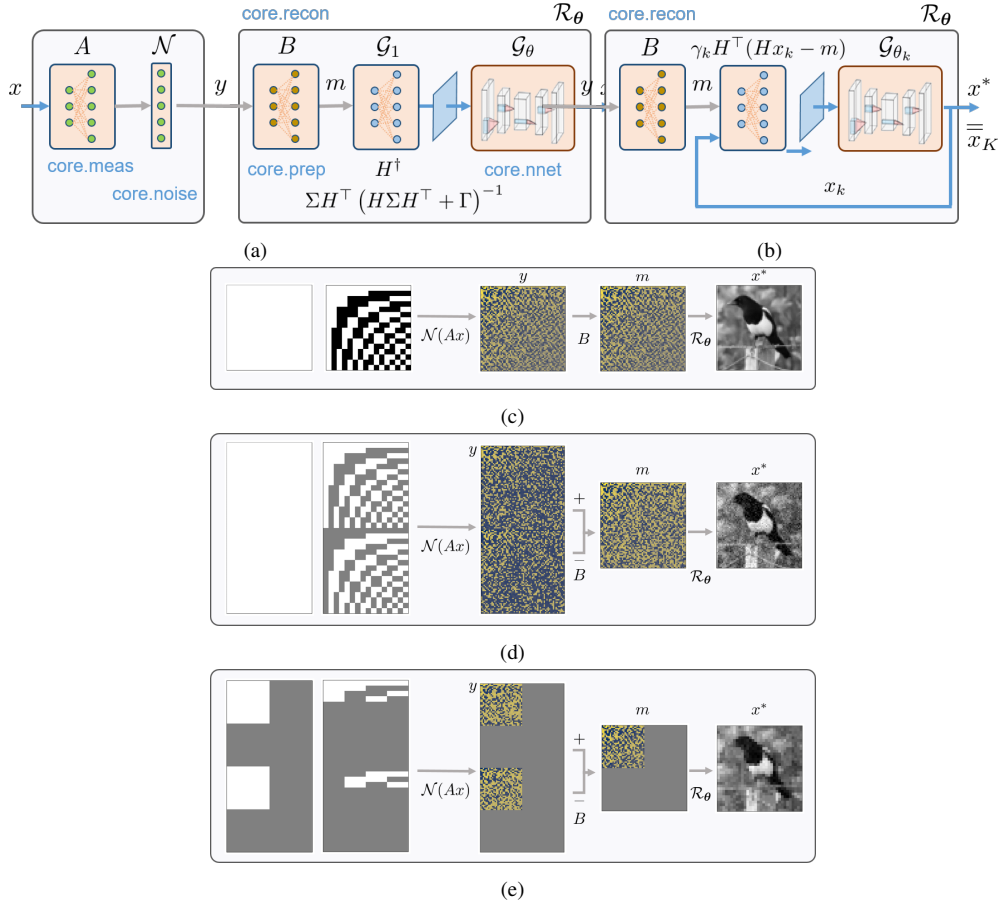


Fig. 2. Typical SPyRiT pipelines involving input of an image $x \in \mathbb{R}^N$, simulation of modulated measurements Ax , application of a noise model \mathcal{N} which leads to the raw measurements $y \in \mathbb{R}^J$. From these, the reconstruction operator \mathcal{R}_θ outputs an estimate x^* of x . **(a)** Post-processing reconstruction approaches corresponding to Eq. (6). All steps are clearly separated and defined independently in the submodules `core.meas`, `core.noise`, and `core.recon`. The reconstruction algorithm can integrate preprocessing from `core.prep`, analytical steps and neural networks from `core.nnet`. **(b)** Iterative reconstruction approaches corresponding to Eq. (7). **(c)** Hadamard acquisitions which cannot be implemented in practice due to negative values in the target acquisition matrix. **(d)** Split Hadamard patterns defined by Eq. (12) with $M = N$ and the corresponding preprocessing $B = [I_N, -I_N]$. Poisson noise is simulated with $\alpha = 100$. **(e)** Square subsampling for split Hadamard acquisition, i.e., Eq. (12) with $M < N$ and the corresponding preprocessing $B = [I_M, -I_M]$. No noise is simulated. **(c-e)** The images on the left correspond to sampling masks. White masks correspond to the case $M = N$ where all measurements are kept, while grey pixels appear in the case of accelerated acquisitions where $M < N$. A sampling mask is a graphical representation of the permutation matrix Q in Eq. (13). Each white pixel of a sampling mask corresponds to the nonzero entry of each of the first M rows of Q . For simplicity, the $N = 64 \times 64$ acquisition matrices used are presented here as $N = 16 \times 16$.

140 **3. Method**

141 *3.1. Overview of the SPyRiT package*

142 SPyRiT has a modular structure with the core functionalities organized in six submodules
 143 (see Fig. 2) that provide classes that all inherit from PyTorch `nn.Module`. The module
 144 `spyrit.core.torch` provides additional auxiliary PyTorch-based functions used throughout
 145 the SPyRiT package.

- 146 • `spyrit.core.meas` provides measurement operators that compute linear measure-
 147 ments corresponding to A in Eq. (2). It also provides the adjoint and pseudo-inverse of A ,
 148 which are at the basis of any reconstruction algorithm.
- 149 • `spyrit.core.noise` provides noise operators corresponding to \mathcal{N} in Eq. (2).
- 150 • `spyrit.core.prep` provides preprocessing operators for the operator B introduced in
 151 Eq. (3). These preprocessing operators can also implement additional processing steps,
 152 such as the normalization of Poisson-corrupted images that vary across a wide range of
 153 intensities.
- 154 • `spyrit.core.nnet` provides neural network operators that correspond to \mathcal{G} in Eq. (6)
 155 or Eq. (10).
- 156 • `spyrit.core.recon` provides the reconstruction operator that correspond to \mathcal{R}_θ .
- 157 • `spyrit.core.train` provides the functionalities to solve the minimization problem
 158 of Eq. (5).

159 *3.2. Poisson-corrupted split Hadamard measurements*

160 To illustrate the capabilities of SPyRiT, we consider Poisson-corrupted split Hadamard measure-
 161 ments

$$y_\alpha \sim \mathcal{P}(\alpha Ax), \quad (11)$$

162 where α (in photons) represents the intensity of the image $x \in [0, 1]^N$. The higher the intensity,
 163 the higher the SNR of the measurements. We chose the acquisition matrix $A \in \mathbb{R}_+^{2M \times N}$, $M \leq N$,
 164 such that the positive and negative components of the target matrix $H \in \mathbb{R}^{M \times N}$ are measured
 165 independently

$$A = \begin{bmatrix} H_+ \\ H_- \end{bmatrix}, \quad (12)$$

166 where $H_\pm = \max(0, \mp H) \in \mathbb{R}_+^{M \times N}$. Choosing $B = [I_N, -I_N]$, we recover $BA = H$. In the case
 167 of accelerated acquisitions for which $M < N$, we choose H as a subsampled (i.e., row-decimated)
 168 Hadamard matrix

$$H = [I_M, 0]QH_\uparrow, \quad (13)$$

169 where $H_\uparrow \in \mathbb{R}^{N \times N}$ represents the full Hadamard matrix, $I_M \in \mathbb{R}^{M \times M}$ the identity matrix, and
 170 $Q \in \{0, 1\}^{N \times N}$ a permutation matrix that ranks the Hadamard coefficients by significance. The
 171 entire process is illustrated in Fig. 2d and Fig. 2e. The acquisition matrix can be defined using the
 172 `meas.HadamSplit` class, while Poisson noise is handled via the `noise.Poisson` class.

173 3.3. Reconstruction algorithms

174 We consider algorithms that fall into different reconstruction strategies (e.g., optimization-based,
175 post-processing and iterative methods, supervised or PnP methods). Given the modularity of
176 SPyRiT, all methods can be easily defined by exploiting the acquisition and denoising operators.
177 The selected methods are:

- 178 • Pseudo-inverse (Pinv), which corresponds to Eq. (8) with \mathcal{G}_θ being the identity.
- 179 • Pseudo-inverse with supervised denoising (Pinv-Net) [21], which corresponds to Eq. (8)
180 where \mathcal{G}_θ is trained using Eq. (5).
- 181 • Pseudo-inverse with PnP denoising (Pinv-PnP), which corresponds to Eq. (8) where \mathcal{G}_θ is
182 trained independently as a denoiser.
- 183 • Supervised denoised completion (DC-Net) [50], which corresponds to Eq. (9) where \mathcal{G}_θ
184 is trained using Eq. (5).
- 185 • Learned proximal gradient descent (LPGD), which corresponds to Eq. (10) where \mathcal{G}_θ is
186 trained using Eq. (5).
- 187 • Proximal gradient descent with PnP denoising (DPGD-PnP), which corresponds to Eq.
188 (10), where \mathcal{G}_θ is trained independently as a denoiser.

189 The Pinv, Pinv-Net and Pinv-PnP methods are all instances of the same class `core.recon.PinvNet`,
190 where the only difference is the denoising layer (the identity for Pinv, UNet [18] trained in a
191 supervised manner for Pinv-Net, and pretrained DR-UNet [34] for Pinv-PnP). The LPGD and
192 DPGD-PnP are also two instances of the same class `recon.LearnedPGD`. All algorithm
193 details are provided in Section A. Note that both PnP methods (i.e., Pinv-PnP, DPGD-PnP) rely on
194 a hyperparameter (ν for Pinv-PnP and μ for DPGD-PnP) that allows the denoising/regularization
195 level to be manually tuned (see Appendix and Sec. 1.1 and 1.2 of Supplement 1).

196 3.4. Example code

197 The code required to run both the simulation and reconstruction with the `pinvNet` network is
198 shown below.

```
199 # Data simulation
200 import math
201 import torch
202 from spyrit.core.meas import HadamSplit
203 from spyrit.core.noise import Poisson
204
205
206 alpha = 100.0
207 h = math.sqrt(N)
208 meas_op = HadamSplit(M, h, Ord_rec)
209 noise_op = Poisson(meas_op, alpha)
210 torch.manual_seed(0)
211 y = noise_op(x) # x is vectorized image
212
213 # Image reconstruction
214 from spyrit.core.recon import PinvNet
215 from spyrit.core.nnet import Unet
216
217 prep_op = SplitPoisson(alpha, meas_op)
218 denoi_net = Unet()
219 full_op = PinvNet(noise_op, prep_op, denoi_net)
220 x_rec = full_op.reconstruct(y)
221
222 # Simulation and reconstruction
```



```
223 torch.manual_seed(0)
224 x_rec_2 = full_op(x)
225
226 (x_rec == x_rec_2).all() # True
227
```

228 The code that generates the masks, acquisition matrices and images in Fig. 2 is provided in the
229 last section of Supplement 1. Multiple examples are provided in the tutorials accessible in [52].

230 3.5. Training

231 All supervised methods (i.e., Pinv-Net, DC-Net, LPGD) are trained by minimizing the mean
232 squared error loss of Eq. (5) over the test dataset (100k images) of the ImageNet ILSVRC2012
233 database [53]. Color images are subject to grayscale transformation, with random crops of size
234 128×128 pixels and normalization to $[-1, 1]$ applied to all images. Measurements are simulated
235 according to Eq. (11) for an image intensity $\alpha = 10$ photons. The minimization problem is solved
236 using the Adam optimizer [54] with a learning rate of 10^{-3} , a batch size of 128 for Pinv-Net and
237 LPGD and 256 for DC-Net, and 30 epochs. The learning rate is decreased by a factor of 0.5
238 every 10 epochs. The weight decay regularization parameter is set to 10^{-7} . The parameters of
239 the optimizer were optimized previously for DC-Net and Pinv-Net [23]. For the PnP methods
240 (i.e., Pinv-PnP and DPGD-PnP), the data driven layers are trained independently as denoisers,
241 see [34] for Pinv-PnP and [55] for DPGD-PnP. The methods adapt to different noise levels by
242 adjustment of a hyperparameter that controls the amount of regularization/denoising (see Sec.
243 1.1 and 1.2 of Supplement 1).

244 4. Results

245 4.1. Simulated data

246 We simulate Hadamard split measurements corrupted by Poisson noise according to Eq. (11) and
247 Eq. (12) for three different image intensities α equal to 2, 10 and 50 photons, which correspond
248 to increasing SNR. Methods are evaluated using the entire evaluation set (50k images) of the
249 ImageNet ILSVRC2012 database [53]. All images are cropped to $N = 128 \times 128$ pixels. The
250 number of measurements is set to $M = 4096$ and a $\times 4$ square subsampling strategy is used
251 (i.e., the measurements correspond to a full acquisition for 64×64 Hadamard patterns). We
252 compare all methods in terms of root mean square error (RMSE), structural similarity index
253 measure (SSIM), and by visual inspection. The hyperparameter of the PnP methods is chosen
254 for each noise level to minimize RMSE and maximize SSIM across a subset of 384 images
255 of the training set of the ImageNet ILSVRC2012 database. When RMSE and SSIM disagree,
256 the hyperparameter was selected by visual inspection, as described in Sections 1.1 and 1.2 of
257 Supplement 1.

258 Table 1 reports RMSE and SSIM for the three noise levels for all methods. For the noise
259 level used for training ($\alpha = 10$ photons), all supervised methods provide similar results in terms
260 of RMSE and SSIM, which are slightly better than for PnP methods. Among PnP methods,
261 Pinv-PnP yields better metrics than DPGD-PnP. Deep learning methods reduce RMSE by up to
262 half compared to the traditional method Pinv. Comparing the results for higher SNR ($\alpha = 50$
263 photons), slightly improved metrics (lower RMSE and higher SSIM) are achieved by deep
264 learning methods with respect to $\alpha = 10$ photons. For lower SNR ($\alpha = 2$ photons), supervised
265 methods (except for DC-Net) approximately double RMSE compared to PnP methods.

266 Figure 3 presents a number of ground truth and reconstructed images. For $\alpha = 10$ photons, all
267 deep learning methods are able to remove noise quite efficiently. Supervised methods lead to
268 sharper images than PnP methods. Pinv-Net and LPGD are more consistent across images than
269 DC-Net, which yields sharper images in some cases and more blurred results in others. LPGD
270 leads to sharper results than Pinv-Net for some images. Pinv-PnP provides a natural texture with

271 low noise but images are less sharp. DC-Net provides the best results in terms of sharpness.
272 For other image intensities, the best results are obtained using PnP methods and DC-Net, with
273 more detail or less noise. For $\alpha = 2$ photons (i.e., lower SNR than training), supervised methods
274 result in noisy images equivalent to Pinv, except for DC-Net which achieves similar results to
275 PnP methods. For $\alpha = 50$ photons (i.e., higher SNR than training) DC-Net performs well. More
276 results can be found in Sec. 1.3 of Supplement 1, including measurements simulated from the
277 human brain image dataset [56].

278 4.2. Experimental data

279 Experimental data is used from the SPIHIM dataset [45], an open-access collection of single-pixel
280 acquisitions that fulfil the FAIR principles. [57]. In particular, we consider the Star Sector
281 resolution target (Thorlabs, R1L1S2P, see top row of Fig. 4) and a tomato slice (see bottom row
282 of Fig. 4), which has a smoother texture and no symmetry. As in Section 4.1, the measurements
283 correspond to a full acquisition with $M = 4096$ split Hadamard patterns of size 64×64 , which
284 correspond to a $\times 4$ square subsampling strategy for a reconstruction with $N = 128 \times 128$ pixels.
285 Figure 4 shows the reconstruction of the Star Sector resolution target and tomato slice. As for the
286 simulated data, Pinv results in noisy images while the data-driven methods efficiently remove
287 noise. For the resolution target, Pinv-Net, LPGD and DPGD-PnP effectively remove noise but
288 lead to artefacts that are especially visible close to the central white disk. DC-Net leads to a
289 more natural texture but slightly blurred. Pinv-PnP yields almost perfect reconstruction. For the
290 tomato slice, supervised methods Pinv-Net and LPGD result in the sharpest images, while the
291 other methods yield images that are excessively blurred. These findings are corroborated by the
292 reconstruction results of other images, which are reported in Section 2 of Supplement 1.

293 5. Conclusion

294 To the best of our knowledge, this is the first time a PyTorch package has been presented to
295 enable reproducible research and benchmarking in the field of single-pixel imaging. The package
296 includes a number of supervised and plug-and-play methods, including post-processing and
297 iterative strategies.

298 We observe that all data-driven methods perform well provided that the image intensity is
299 similar or higher to the training phase. However, most of the data-driven methods are not robust
300 if the intensity is lower than the training phase, which is often the case in practice. This suggests
301 that comparative studies should carefully address this kind of discrepancy. In this regard, the
302 versatility of PnP methods is an advantage via manual tuning of the hyperparameter with respect
303 to the noise level. The hyperparameter, however, has a significant impact on reconstruction
304 quality and therefore requires careful selection. Among the supervised methods, DC-Net appears
305 to be robust to deviations in the noise level, almost comparable to PnP methods and without
306 hyperparameter selection. This is due to the fact that DC-Net includes a denoising step that
307 removes noise prior to reconstruction. We also observe that the data-driven methods trained on
308 simulations perform very well on experimental data, provided that the noise level corresponds
309 to that of the training phase, which indicates that there is not a large model mismatch between
310 simulations and experiments.

311 The modularity and versatility of SPyRiT make it suitable for further studies beyond this work,
312 such as the comparison or learning of acquisition matrices, noise models, or reconstruction
313 algorithms. Current developments include hyperspectral imaging and dynamic imaging [58].
314 While SPyRiT has been designed for single-pixel imaging, it may also benefit other modalities,
315 in particular in the field of computational optics where the formation models are often in the
316 form of Eq. (2). Computational ghost imaging [59] is of particular interest due to its equivalence,
317 from an optical perspective, to single-pixel imaging.

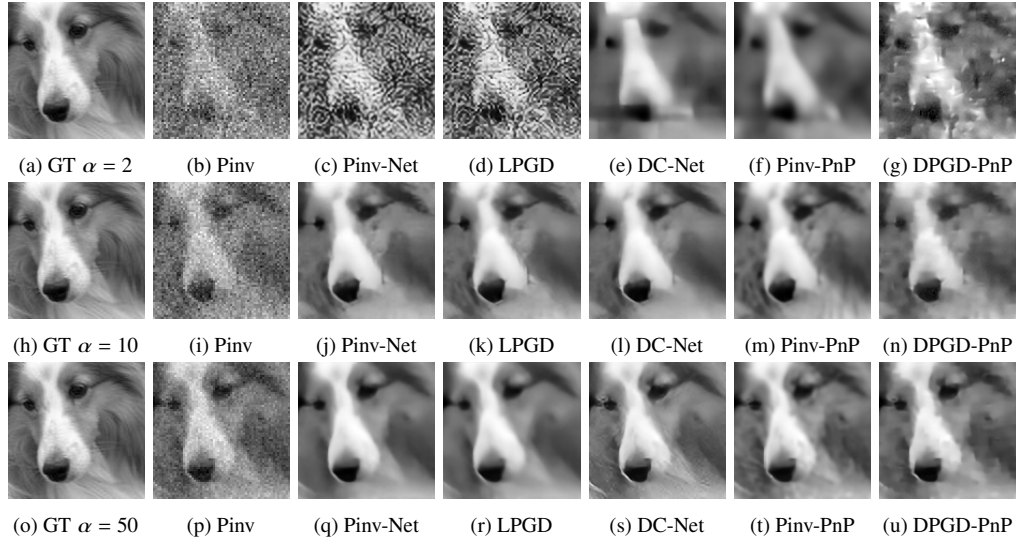


Fig. 3. Ground truth (GT) and reconstructed images obtained from measurements simulated from the ImageNet ILSVRC2012 evaluation set. All supervised methods are trained with an image intensity $\alpha = 10$ photons and tested for $\alpha = 2$ (first row), $\alpha = 10$ (second row), and $\alpha = 50$ (third row) photons. The measurements correspond to Hadamard split acquisitions with a $\times 4$ square subsampling strategy. The images are reconstructed from $M = 4096$ measurements, with the number of pixels set to $N = 128 \times 128$. The Pinv-PnP hyperparameter is set to $\nu = 115$ for $\alpha = 2$; $\nu = 45$ for $\alpha = 10$; and $\nu = 20$ for $\alpha = 50$. The DPGD-PnP hyperparameter is set to $\mu = 6000$ for $\alpha = 2$; $\mu = 3500$ for $\alpha = 10$; and $\mu = 1500$ for $\alpha = 50$.

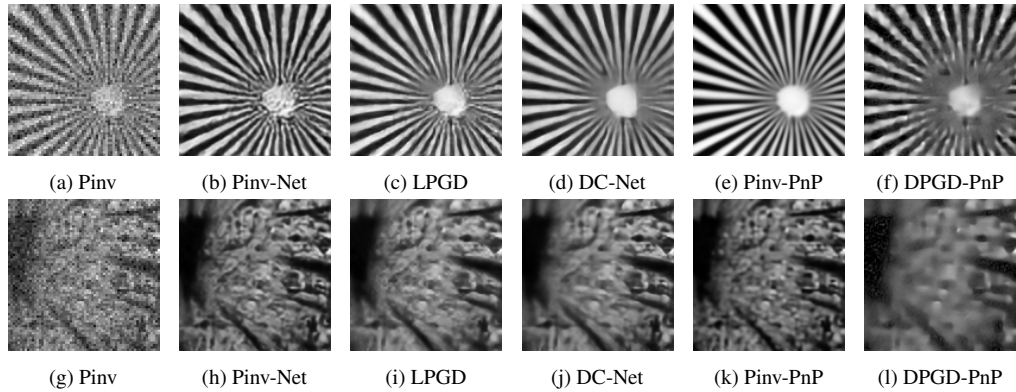


Fig. 4. Experimental reconstruction results for the Star Sector resolution target and tomato slice. The measurements correspond to Hadamard split acquisitions using a $\times 4$ square subsampling strategy. The images are reconstructed from $M = 4096$ measurements, with the number of pixels set to $N = 128 \times 128$. The Pinv-PnP hyperparameter is set to $\nu = 55$ for the resolution target; and $\nu = 35$ for the tomato slice. The DPGD-PnP hyperparameter is set to $\mu = 4000$ for the resolution target; and $\mu = 4000$ for the tomato slice.

Table 1. Reconstruction metrics obtained for measurements simulated using the evaluation set of the ImageNet ILSVRC2012 database for three image intensities α . All data-driven reconstruction methods were trained considering $\alpha = 10$ photons. Values correspond to mean (standard deviations) across images. For DPGD-PnP, standard deviations are not shown because metrics were obtained from only 384 images, given its higher computational cost. Pinv leads to highly corrupted images for some cases, resulting in NaN values for SSIM.

Methods	RMSE	SSIM
$\alpha = 2$		
Pinv	1.09 (0.64)	NaN
Pinv-Net	0.81 (0.51)	0.19 (0.14)
LPGD	0.84 (0.51)	0.18 (0.12)
DC-Net	0.41 (0.19)	0.41 (0.19)
Pinv-PnP ($\nu = 115$)	0.34 (0.16)	0.42 (0.19)
DPGD-PnP ($\mu = 6000$)	0.45 (-)	0.26 (-)
$\alpha = 10$ (as for training)		
Pinv	0.53 (0.29)	NaN
Pinv-Net	0.25 (0.14)	0.61 (0.16)
LPGD	0.26 (0.14)	0.61 (0.16)
DC-Net	0.26 (0.14)	0.61 (0.17)
Pinv-PnP ($\nu = 50$)	0.27 (0.14)	0.56 (0.18)
DPGD-PnP ($\mu = 3500$)	0.30 (-)	0.46 (-)
$\alpha = 50$		
Pinv	0.31 (0.15)	NaN
Pinv-Net	0.22 (0.14)	0.68 (0.17)
LPGD	0.23 (0.14)	0.66 (0.18)
DC-Net	0.25 (0.15)	0.71 (0.14)
Pinv-PnP ($\nu = 20$)	0.23 (0.13)	0.68 (0.15)
DPGD-PnP ($\mu = 1500$)	0.22 (-)	0.67 (-)

318 **Appendix**

319 **A. Algorithm details**

320 *A.1. Reconstruction problem*

321 Regularized methods consist in defining the estimate as a solution to the minimization recon-
322 struction problem

$$\min_x \mathcal{D}(m, Hx) + g_\mu(x), \quad (14)$$

323 where \mathcal{D} is the data fidelity term and g_μ is a regularization term that depends on the hyperparameter
324 (e.g., regularization parameter) $\mu > 0$. We choose the weighted least-squares data fidelity term

$$\mathcal{D}(m, Hx) = \frac{1}{2} \|m - Hx\|_{\Gamma^{-1}}^2, \quad (15)$$

325 where $\Gamma \in \mathbb{R}^{M \times M}$ represents the noise covariance, which is assumed to be diagonal for
326 independent measurements, i.e., $\Gamma = \text{diag}(\sigma_1^2, \dots, \sigma_M^2)$ with $\sigma_i^2 > 0$ the variance of the i -th
327 measurement. For the Poisson-corrupted split measurements described in Section 3.2, the
328 variance can be approximated as

$$\sigma_i^2 = \frac{1}{4}(m_i^+ + m_i^-), \quad (16)$$

329 where m_i^+ and m_i^- represent, respectively, the raw measurements obtained from the positive and
330 negative component of the i -th target pattern [23].

331 *A.2. Closed-forms: pseudo-inverse and Tikhonov regularization*

332 Without regularization (i.e., when $g_\mu(x) = 0$) and in the absence of noise model (i.e., choosing
333 $\Gamma = I$), the solution to the problem in Eq. (14) is given by the pseudo-inverse approach defined
334 by Eq. (8).

335 When $g_\mu(x) = \|x\|_{\Sigma^{-1}}^2$, where Σ represents the image covariance, the solution to the problem
336 in Eq. (14) admits the closed form solution given by Eq. (9). The DC-Net method is of the
337 form of Eq. (6) with \mathcal{R} given in Eq. (9). In this approach, the image covariance Σ , which has
338 been computed on the ImageNet ILSVRC2012 database (see [45, Sec. 3.3]), and the learnable
339 parameters of \mathcal{G}_θ have been downloaded from [60].

340 *A.3. Proximal gradient descent*

341 A common iterative method used to solve the minimization problem in Eq. (14) with data-fidelity
342 term given in Eq. (15) is the proximal gradient descent algorithm (a.k.a. forward-backward
343 splitting algorithm) [61]. For this problem, iterations are given by

$$x_{k+1} = \text{prox}_{\gamma g_\mu}(x_k - \gamma H^\top \Gamma^{-1}(Hx_k - m)), \quad (17)$$

344 where $\text{prox}_{\gamma g}$ is the proximity operator of g (see [61]) and γ is a step size. The sequence $(x_k)_{k \in \mathbb{N}}$
345 generated by Eq. (17) converges with rate $O(1/k)$ using a fixed step size $\gamma \in (0, \beta^{-1})$, where

$$\beta = \|\Gamma^{-1/2} H H^\top \Gamma^{-1/2}\|_2 = \|H^\top \Gamma^{-1} H\|_2, \quad (18)$$

346 with $\|\cdot\|_2$ the spectral norm (i.e., the largest singular value of its argument).

347 *A.4. Step size for a Hadamard matrix*

348 To compute the step-size γ in Eq. (17), it is necessary to compute β . In the case when H is
349 the Hadamard matrix, we have $H^\top H = NI_N$. Hence, using Eq. (18), we have $\beta = N\|\Gamma^{-1}\|_S =$
350 $N \max_i \sigma_i^{-1}$, so

$$\beta^{-1} = \frac{\min_i \sigma_i^2}{N}. \quad (19)$$

351 **A.5. Learned proximal gradient descent**

352 The LPGD method considers the proximal iteration of Eq. (17), where the proximity operator of
353 g_μ is replaced by a neural network \mathcal{G}_{θ_k} [51], i.e.,

$$x_{k+1} = \mathcal{G}_{\theta_k} (x_k - \gamma H^\top (Hx_k - m)). \quad (20)$$

354 To limit the number of parameters, the weights of the neural network are shared across iterations,
355 i.e., for every k , $\mathcal{G}_{\theta_k} \equiv \mathcal{G}_\theta$. Since the neural networks of LPGD are learned end-to-end, we only
356 unroll Eq. (20) over a fixed number of iterations K .

357 In this context, two hyperparameters need to be tuned: the number of iterations K and the step
358 size γ . The number of iterations is commonly chosen between 3 and 10, as a trade-off between
359 performance and computational cost. We have tested both fixed and decreasing step sizes, i.e.,
360 $\gamma_k = \tau \gamma_{k-1}$ with a decaying multiplicative factor $0 < \tau \leq 1$. The step size has been initialized to
361 the inverse of the Lipschitz constant given in Eq. (19), as suggested by optimization theory (see
362 Appendix A.4). We have tested different values for the number of iterations (3, 6 and 10) and
363 different decaying factors (0.1, 0.5, 0.9, and 1). The best results were obtained for $\tau = 0.9$, and
364 as little difference was found in terms of number of iterations, we selected $K = 3$ (results not
365 shown).

366 **A.6. Dual PGD network**

367 We consider the LPGD iteration given in Eq. (20), where \mathcal{G}_{θ_k} is trained as a denoiser independent
368 from the measurement model and is itself an unfolded algorithm that mimics the proximity
369 operator of g_μ . Specifically, we consider the case when $g_\mu = \iota_{[-1,1]} + \lambda \|L \cdot\|_1$ with $L: \mathbb{R}^N \rightarrow \mathbb{R}^S$
370 a linear sparsifying operator. In this case the proximity operator of g_μ can be computed using the
371 dual PGD algorithm [61]. Within a deep learning framework, only a fixed number of iterations
372 of the dual PGD algorithm are unrolled, and the operator L can be learned (and changed for each
373 layer), leading to a Dual PGD network dubbed DPGD-PnP (see [55, 62]).

374 The DPGD-PnP network is composed of 20 layers, and the linearity associated with each layer
375 corresponds to a convolution with 64 features. We trained the network using the ImageNet test
376 dataset.

377 Since this approach is based on the LPGD iteration from Eq. (20), the step size is chosen
378 as per Appendix A.4. The main advantage compared to the supervised approaches is that the
379 training is independent of the measurement model. However, a large number of iterations must
380 be considered. We choose $K_{\max} = 101$ with a stopping criterion $\|x_{k+1} - x_k\| < 10^{-4} \|x_k\|$ in case
381 convergence is reached before K_{\max} iterations.

382 **Funding.** Institut Universitaire de France; Agence Nationale de la Recherche (ANR-11-LABX-0063,
383 ANR-22-CE19-0030-01).

384 **Disclosures.** The authors declare no conflicts of interest.

385 **Data Availability Statement.** The code and data are provided in [63].

386 **Supplemental document.** See Supplement 1 for supporting content.

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