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On the benefit of adversarial training for monocular depth estimation

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A B S T R A C T
In this paper we address the benefit of adding adversarial training to the task of monocular depth estimation. A model can be trained in a self-supervised setting on stereo pairs of images, where depth (disparities) are an intermediate result in a right-to-left image reconstruction pipeline. For the quality of the image reconstruction and disparity prediction, a combination of different losses is used, including L1 image reconstruction losses and left–right disparity smoothness. These are local pixel-wise losses, while depth prediction requires global consistency. Therefore, we extend the self-supervised network to become a Generative Adversarial Network (GAN), by including a discriminator which should tell apart reconstructed (fake) images from real images. We evaluate Vanilla GANs, LSGANs and Wasserstein GANs in combination with different pixel-wise reconstruction losses. Based on extensive experimental evaluation, we conclude that adversarial training is beneficial if and only if the reconstruction loss is not too constrained. Even though adversarial training seems promising because it promotes global consistency, non-adversarial training outperforms (or is on par with) any method trained with a GAN when a constrained reconstruction loss is used in combination with batch normalisation. Based on the insights of our experimental evaluation we obtain state-of-the-art monocular depth estimation results by using batch normalisation and different output scales.

1. Introduction
We are interested in estimating depth from single images. This is fundamentally an ill-posed problem, since a single 2D view of a scene can be explained by many 3D scenes, among others due to scale ambiguity. Therefore the corresponding 3D scene should be estimated – implicitly – by looking at the global scene context. Using the global context, a model prior can be estimated to reliably retrieve depth from a single image.

To take into account global scene context for single image depth estimation, elaborate image recognition models have been developed (Eigen et al., 2014; Godard et al., 2017; Saxena et al., 2006). Currently used deep convolutional networks (ConvNets) have enough capacity to understand the global relations between pixels in the image as well as to encode the prior information. However, they are only trained with combinations of per-pixelwise losses.

Generative Adversarial Networks (GANs) (Goodfellow et al., 2014; Isola et al., 2017) force generated images to be realistic and globally coherent. They do so by introducing an adaptable loss, in the form of a neural discriminator network that penalises generated output that looks different from real data. GANs have seen much research attention in recent years, with ever increasing quality of the generated data (e.g. Karras et al. (2019)). Moreover, they have shown success in many tasks, including image reconstruction (Isola et al., 2017), image segmentation (Ghafoorian et al., 2018), novel viewpoint estimation (Galama and Mensink, 2018) and binocular depth estimation (Pilzer et al., 2018). In this paper, we add an adversarial discriminator network to an existing monocular depth estimation model to include a loss based on global context.

Training deep ConvNets requires large datasets with corresponding depth data, preferably dense depth data where ground truth depth is available per pixel. These are not always easy to obtain, either due to a complicated acquisition setup or due to sparse depth data of LiDaR sweeps. To circumvent this, depth prediction has recently been formulated as a novel viewpoint generation task from stereo imagery, where depth is never directly estimated, but just the valuable intermediate in an image reconstruction pipeline. Godard et al. (2017) start from a stereo pair of images, and use the left image to estimate the disparities from the right-to-the-left image, which is combined with the right image to reconstruct the left image (see Fig. 1). Due to the constrained image reconstruction setting, disparities are learned from

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a single view. We use this model as our baseline and extend it with a
discriminator network, which we train in an adversarial setup.

Previous literature (Godard et al., 2017; Yang et al., 2018; Luo
et al., 2016; Mayer et al., 2016) shows impressive performance of depth
estimation using mostly engineered photometric and geometric losses.
However, most of these loss functions are defined as a sum over per
pixel loss functions. The global consistency of the scene context is not
taken into account in the loss formulation. We address the question:
“To what extent can monocular depth estimation benefit from adversarial
training?” We do so by studying the influence of adversarial learning
on several combinations of photometric and geometric loss functions.

2. Related work

Monocular depth estimation. Estimating depth from single images is fund-
damentally different from estimating depth from stereo pairs, because it
is no longer possible to triangulate points. In a monocular setting,
contextual information is required, e.g. texture variation, occlusions,
and scene context. These cannot reliably be detected from local image
patches. For example, a patch of blue pixels could either represent
distant sky, or a nearby blue coloured object. The global picture thus
has to be considered. Global context information can for example be
modelled by using manually engineered features (Saxena et al., 2009),
or by using CNNs (Eigen et al., 2014).

Depth ground truth is expensive and time-consuming to obtain, and
the readings might be inaccurate, e.g. due to infrared interference or
due to surface specularities. An alternative is to use self-supervised
depth estimation (Garg et al., 2016; Godard et al., 2017, 2018),
where training data consists of pairs of left and right images. A disparity
prediction model can be trained, to warp the left image into the right
image, using photometric reconstruction losses. Depth can be recovered
from the disparities, by using the camera intrinsics, making depth
ground truth data unnecessary at train time. While stereo pairs are
necessary during training, during test time depth can be predicted from
a single image. In this work we use the work of Godard et al. (2017) as
a baseline. Their follow-up work is also concerned with depth estimation,
yet based on temporal sequences of (monocular) frames (Godard et al.,
2018). The scope of our paper is on stereoscopic learning of depth.

GANs for image generation. Depth estimation from single images can be
formulated as an image warping or image generation task. Often
image generation is done by means of encoder–decoder networks that
output newly generated images. Encoder–decoder networks trained
using L1 or L2 produce blurry results (Pathak et al., 2016; Zhao et al.,
2017), since output pixels are penalised conditioned on their respective
input pixels, but never on the joint configuration of the output pixels.
GANs (Goodfellow et al., 2014; Mirza and Osindero, 2014; Isola et al.,
2017) counteract this by introducing a structured high-level adaptable
loss. GANs are used in tasks where generating globally coherent images
is important. Since monocular depth estimation is largely dependent
on how well global contextual information is extracted from the input
view, there is reason to believe GANs can be of benefit.

Pairing the high-level adversarial loss with a low-level reconstruction
loss such as L1 may boost performance even more (Isola et al.,
2017). This may be due to the fact that the adversarial loss punishes
high-level detail, but only slowly updates low-level detail. Combin-
ing adversarial losses and pixel-based local losses has been shown to
work well for a number of tasks, including novel viewpoint estima-
tion (Huang et al., 2017; Wu et al., 2016; Galama and Mensink, 2018),
predicting future frames in a video (Yin et al., 2018; Mathieu et al.,
2015), and image inpainting (Pathak et al., 2016).

GANs for depth estimation. Adversarial losses have already been ex-
plored for depth estimation. Chen et al. (2018) shows that adversarial
training can be beneficial when directly regressing on depth from single
images using ground-truth depth data. The authors use a CNN and a
CNN-CRF architecture using either L1 or L2 norm as similarity
metrics for the predicted depths. Since they only ever use single
images during training, they do not exploit scene geometry for more
involved geometric losses. Kumar et al. (2018) predict depth maps from
monocular video sequences and successfully use an adversarial network
to promote photo-realism between frames. Their generator is com-
posed of two separate networks: A depth network and a pose network.
Together these networks enable the authors to generate frames over
time. Compared to the current work the problem is less constrained,
because the static scene assumption is violated. That is, objects in
the scene may themselves move between frames. Pilzer et al. (2018)
suggest to use a cycled architecture for estimating depth, in which two
generators and two discriminators jointly learn to estimate depth. Their
half-cycle architecture is close to our approach, since it uses a single
discriminator. However, the generator requires the input of both left
and right images to predict a disparity map and even then does not
explicitly enforce consistency between the two images. Concurrently
with our research is the work of Aleotti et al. (2018), where the method
of Godard et al. (2017) is extended with a vanilla GAN. They address
the weighting of loss components and find that a subtle adversarial
loss can possibly yield improved performance, albeit marginally.
In our experiments we find the opposite, none of the used GAN variants
improve performance, and we show that small variations of perfor-
mane could also be explained by initialisation or attributed to the use
of batch normalisation. Unlike the methods above the purpose of the
current work is to evaluate adversarial approaches when constrained
reconstruction losses are used.

We evaluate different GAN objectives for depth estimation, in part
based on the results of Lucic et al. (2018), who conclude that no variant
is (necessarily) better than others, given a sufficiently large computa-
tional budget and extensive hyper-parameter search. We compare the
following GAN variants:

1. Vanilla GAN, with a PatchGAN (Isola et al., 2017) discriminator;
2. Gradient-Penalty Wasserstein GANs (WGAN-GP) (Arjovsky et al.,
2017; Gulrajani et al., 2017), which minimises the Wasserstein
distance, to overcome the saturating loss of the original GAN
formulation;
3. Least Square GANs (LSGAN) (Mao et al., 2017), where the
sigmoid real or fake prediction is replaced by an L2-loss.

While GANs provide a powerful method to output realistic data with
an adaptable loss, they are notoriously difficult to train stably (Salimans
et al., 2016). Many strategies to improve training stability of GANs have
been proposed, including using feature matching (Ghafoorian et al.,
2018), using historical averaging (Shrivastava et al., 2017), or adding
batch normalisation (Ioffe and Szegedy, 2015). We include the latter in
our GAN variants; initial results have shown that batch normalisation is
beneficial for vanilla GANs and LSGANs to counteract internal covariate
shift.
3. Method

The baseline of our single depth estimation model is the reconstruction-based architecture for depth estimation from Godard et al. (2017), which we describe first. Then, we extend this baseline with an adversarial discriminator network.

Depth from image reconstruction. The problem of estimating depth from single images could be formulated as an image reconstruction task, like in Garg et al. (2016), where a generator network takes in a single left view image and outputs the left-to-right disparity. The right image is reconstructed from the left input image and the predicted disparity. As a consequence this network could be trained from rectified left and right image pairs, without requiring ground-truth depth-maps. At test time depth estimation is based on the disparity predicted from the (single) left image, see Fig. 1.

Godard et al. (2017) improve on the work of Garg et al. (2016) by using both right-to-left and left-to-right disparities and by using a bilinear sampler (Jaderberg et al., 2015) to generate images, which makes the objective fully differentiable.

We first describe in detail the method of Godard et al. (2017), our baseline: The generator \( G \) uses the left image of the pair to reconstruct both the left and right images. Consider a left image \( I^l \) and a right image \( I^r \). Image \( I^r \) will be used as the sole input to the generator \( G \). The generator \( G \), however, outputs two disparities \( d^l \) and \( d^r \). Using left-to-right disparity \( d^r \) the right image \( I^r \) can be reconstructed, using warping method \( f_w \):
\[
\hat{I}^r = f_w(d^r, I^l)
\]  
And similarly, the reconstructed left image \( \hat{I}^l \), is obtained by:
\[
\hat{I}^l = f_w(d^l, I^r)
\]  
A good generator \( G \) should predict \( d^l \), \( d^r \) such that the reconstructed images \( (\hat{I}^l \) and \( \hat{I}^r \) are close to the original image pair \((I^l \) and \( I^r \)). To measure this several image reconstruction losses are used.

Image reconstruction losses. The quality of the reconstruction is based on multiple loss components, each with different properties for the total optimisation process. We combine:

1. L1 loss to minimise the absolute per-pixel distance:
\[
\mathcal{L}_{l1} = \frac{1}{N} \sum_i \|I_{ij} - \hat{I}_{ij}\|_1
\]  
Note that \( L_1 \) has been outperformed L2 (Zhao et al., 2017).

2. Structural similarity (SSIM) reconstruction loss to measure the perceived quality (Wang et al., 2004):
\[
\mathcal{L}_s = \frac{1}{N} \sum_i (1 - \text{SSIM}(I_{ij}, \hat{I}_{ij}))
\]  
\[
\text{SSIM(x,y)} = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}
\]  
where illumination \( \mu \) and signal contrast \( \sigma \) are computed around centre pixels \( x \) and \( y \), \( \mu_x = 0.01 \) and \( \sigma_x = 0.03 \) overcome divisions by (almost) zeros, these values are set in line with Godard et al. (2017) and Yang et al. (2018).

3. Left–Right Consistency Loss (LR), which enforces the consistency between the predicted left-to-right and right-to-left disparity maps:
\[
\mathcal{L}_{lr} = \frac{1}{N} \sum_i |d_{ij} - d_{ij}^r|
\]  

4. Disparity Smoothness Loss, which forces smooth disparities, i.e. small disparity gradients, unless there is an edge, therefore using an edge-aware L1 smoothness loss:
\[
\mathcal{L}_{disp} = \frac{1}{N} \sum_i |\partial_x d_{ij}| \exp(-\|\partial_x \hat{I}_{ij}\|) + |\partial_y d_{ij}| \exp(-\|\partial_y \hat{I}_{ij}\|)
\]  

since the generator outputs disparities at different scales, this loss is normalised by \( \frac{1}{N} \) at scale \( s \) to normalise the output ranges.

In Yang et al. (2018) an occlusion loss component was suggested in addition to the other loss terms. Initial experimentation shows no clear benefit of using it for our set-up. Results with the occlusion loss can be found in the supplementary material.

The generator network outputs scaled disparities at intermediate layers of the decoder when it is upsampling from the bottleneck layer. For each subsequent scale, height and width of the output image is halved. At each scale the reconstruction loss is computed, and the final reconstruction loss is a combination of the losses at the different scales \( s \):
\[
\mathcal{L}_{rec} = \sum_s \mathcal{L}_s
\]  
\[
\mathcal{L}_s = \gamma_s \mathcal{L}_{l1} + \gamma_s \mathcal{L}_s + \gamma_w + \gamma_{disp} \frac{1}{s^2} \mathcal{L}_{disp}
\]  
where \( \gamma \) weights the influence of each loss component. For each loss component we use the reconstruction of the left and right image, which are defined symmetrically.

Adversarial training for single image depth estimation. We extend the baseline model by a single discriminator network. The discriminator network is tasked with discerning between fake and real images on the right side. The schematic is shown in Fig. 1, by the green discriminator.

For adversarial training, we combine the reconstruction loss \( \mathcal{L}_{rec} \) with the loss functions belonging to specific GAN variants. Note that unlike the original formulation of GANs actual data, in the form of the left image \( I^l \), is fed to the generator, not noise \( z \) (Mirza and Osindero, 2014). The generator \( G \) produces two disparities \( d^l \) and \( d^r \). However the discriminator \( D \) is only presented with the right image \( \hat{I}^r = f_w(d^r, I^l) = f_w(G(I^l), I^l) \) constructed from \( d^r \). Thus the discriminator \( D \) examines only (reconstructed) right images \( I^r \) and \( \hat{I}^r \), to tell apart. This leads to the following losses:

1. Vanilla GAN:
\[
\mathcal{L}_w^G = -\mathbb{E}[\log D(\hat{I}^r)]
\]  
\[
\mathcal{L}_w^G = \mathbb{E}[\log D(I^r) + \log(1 - D(\hat{I}^r))]
\]

2. LS-GAN:
\[
\mathcal{L}_w^L = \frac{1}{2} \mathbb{E}[\left( D(\hat{I}^r) - 1 \right)^2]
\]  
\[
\mathcal{L}_w^L = \frac{1}{2} \mathbb{E}[\left( D(I^r) - 1 \right)^2 + D(\hat{I}^r)^2]
\]

3. WGAN:
\[
\mathcal{L}_w^W = \mathbb{E}[D(\hat{I}^r)]
\]  
\[
\mathcal{L}_w^W = \mathbb{E}[D(I^r) - D(\hat{I}^r)] + \lambda Q_{GP}
\]
where \( Q_{GP} \) denotes the gradient penalty with \( \lambda = 10 \) from WGAN-GP (Gulrajani et al., 2017); and where the generator follows the NS-GAN loss (Goodfellow et al., 2014).

The final loss used for training the generator is:
\[
\mathcal{L} = \mathcal{L}_{rec} + \phi_\theta \mathcal{L}_w^G [\mathcal{L}_{l1, ls, w}]
\]
which combines the reconstruction loss \( \mathcal{L}_{rec} \) with the generator part of the GAN loss \( \mathcal{L}_w^G \), where \( \phi_\theta = 0.1 \) weights its influence.

Evaluation at test time. At test time only the generator is used to predict the right-to-left disparity \( d^l \) at the finest scale, which has the same resolution is the input image. The predicted disparity is transformed into a depth map by using the known camera intrinsic and extrinsic parameters.
Table 1
Evaluation of robustness against initialisation of the networks. Both the baseline model – our implementation of Godard et al. (2017)’s model – and the LSGAN model are trained 10 times. The results indicate that the models are robust against initialisation, albeit some minor variations in the performance remains.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>S</th>
<th>R</th>
<th>Rlog</th>
<th>d1</th>
<th>d2</th>
<th>d3</th>
<th>Lower is better</th>
<th>Higher is better</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>min</td>
<td>0.141</td>
<td>1.163</td>
<td>5.639</td>
<td>0.236</td>
<td>0.806</td>
<td>0.926</td>
<td>0.967</td>
<td>0.967</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.143</td>
<td>1.227</td>
<td>5.732</td>
<td>0.240</td>
<td>0.811</td>
<td>0.929</td>
<td>0.969</td>
<td>0.969</td>
</tr>
<tr>
<td></td>
<td>avg</td>
<td>0.142</td>
<td>1.195</td>
<td>5.681</td>
<td>0.238</td>
<td>0.809</td>
<td>0.927</td>
<td>0.968</td>
<td>0.968</td>
</tr>
<tr>
<td></td>
<td>std</td>
<td>0.001</td>
<td>0.017</td>
<td>0.027</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>LSGAN</td>
<td>min</td>
<td>0.130</td>
<td>1.010</td>
<td>5.359</td>
<td>0.222</td>
<td>0.819</td>
<td>0.936</td>
<td>0.972</td>
<td>0.972</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.135</td>
<td>1.053</td>
<td>5.417</td>
<td>0.227</td>
<td>0.823</td>
<td>0.938</td>
<td>0.974</td>
<td>0.974</td>
</tr>
<tr>
<td></td>
<td>avg</td>
<td>0.133</td>
<td>1.038</td>
<td>5.388</td>
<td>0.225</td>
<td>0.821</td>
<td>0.937</td>
<td>0.973</td>
<td>0.973</td>
</tr>
<tr>
<td></td>
<td>std</td>
<td>0.001</td>
<td>0.014</td>
<td>0.019</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 2
Baseline method performance comparison between different generator architecture backbones, VGG and ResNet variants. While the ResNet-50 architecture yields best performance, we use VGG for fair comparison.

<table>
<thead>
<tr>
<th>#Parm</th>
<th>A</th>
<th>S</th>
<th>R</th>
<th>Rlog</th>
<th>d1</th>
<th>d2</th>
<th>d3</th>
<th>Lower is better</th>
<th>Higher is better</th>
</tr>
</thead>
<tbody>
<tr>
<td>VGG</td>
<td>31.6M</td>
<td>0.142</td>
<td>1.200</td>
<td>5.694</td>
<td>0.239</td>
<td>0.809</td>
<td>0.927</td>
<td>0.967</td>
<td>0.967</td>
</tr>
<tr>
<td>RN-18</td>
<td>20.2M</td>
<td>0.146</td>
<td>1.260</td>
<td>5.771</td>
<td>0.243</td>
<td>0.801</td>
<td>0.924</td>
<td>0.967</td>
<td>0.967</td>
</tr>
<tr>
<td>RN-50</td>
<td>43.9M</td>
<td>0.123</td>
<td>0.936</td>
<td>5.145</td>
<td>0.216</td>
<td>0.843</td>
<td>0.943</td>
<td>0.975</td>
<td>0.975</td>
</tr>
<tr>
<td>RN-101</td>
<td>62.9M</td>
<td>0.124</td>
<td>0.971</td>
<td>5.280</td>
<td>0.219</td>
<td>0.840</td>
<td>0.942</td>
<td>0.974</td>
<td>0.974</td>
</tr>
</tbody>
</table>

4. Experiments

In this section we experimentally evaluate the proposed GAN models on two public datasets KITTI and CityScapes.

4.1. Setup

Dataset. For the main set of experiments we use the KITTI (Geiger et al., 2013) dataset, which contains image pairs of a car driving in various environments, from highways to city centres to rural roads. We follow the Eigen data split (Eigen et al., 2014) to compare fairly against other methods, which uses 22.6K training images, 888 validation images and 697 test images, which are resized to 256 × 512. During training no-depth ground truth is used, only the available stereo imagery. For evaluation the provided velodyne laser data is used.

To test if the results generalise to another dataset, we use the CityScapes dataset (Cordts et al., 2016). This dataset consists of almost 25 thousand images, with 22.9K training images, 500 validation images and 1525 test images. Visual inspection of the CityScapes dataset reveals two things that have consequences for data pre-processing. First, some images contain artefacts at the top and bottom of the images. Second, both left and right cameras capture part of the car on which they are mounted. To compensate the top 50 and bottom 224 rows of pixels are cropped. Cropping is also performed at the sides of the images to retain width and height ratios.

Implementation details. The generator-only model from Godard et al. (2017) is used as a baseline.\(^1\) For all experiments we use an adapted VGG30 generator network architecture, with ~31.6M parameters, for fair comparison with other methods (Godard et al., 2017; Pilzer et al., 2018).

All models are trained for 50 epochs, in mini-batches of 8, with the Adam optimiser (Kingma and Ba, 2014) The initial learning rate \(\gamma = \lambda_0\) is set to \(10^{-4}\), and updated using a plateau scheduler (Radford et al., 2015). Data augmentation is done in online fashion, including gamma, brightness, and colour shifts and horizontal flipping. In case of the latter left and right images are swapped in order to preserve their relative position. Based on recommendations from previous works and some initial experiments, we set \(\gamma_L = 0.15\), \(\gamma_R = 0.85\), \(\gamma_{LR} = 1.0\), \(\gamma_{disp} = 0.1\), \(\phi_G = 0.1\).

The discriminators for Vanilla GAN and LSGAN are convolutional networks with five layers and for WGAN-GP a 3-layer fully-connected network was used.

Evaluation. At test times disparities are warped into depth maps, and the predicted depth is bounded between 0 and 80 m, which is close to the maximum in the ground truths. Similar to other methods we vertically centre-crop images, see e.g. Garg et al. (2016). Ground truth depth data of the Eigen split is sparse. For quantitative evaluation we use a set of common metrics (Eigen et al., 2014; Godard et al., 2017; Pilzer et al., 2018; Yang et al., 2018): Absolute Relative Distance (ARD), Squared Relative Distance (SRD), Root Mean Squared Error (RMSE), log Root Mean Squared Error (log RMSE), and accuracy within threshold \(t = 0.141 + \delta, \delta \in [1.25, 1.25^2, 1.25^3]\).

Note that the disparity of pixels on the side of the image is ill-defined, the so-called disparity ramps. To compensate we use the test image \(I^1\) and its flipped version \(I^{1-f}\) to obtain disparity maps \(d^1\) and \(d^{1-f}\), the latter is flipped again to align with \(d^1\). Both have a disparity ramp, yet on opposite sides of the disparity map. Therefore we use \(d^2\), flipped \((d^{2-f})\) for the 5% outer right (left) columns, and average predictions everywhere else.

Initialisation and backbone. In this set of initial experiments we study the robustness of our models to initialisation and the influence of the backbone architecture.

In this first experiment we study the robustness of our models with respect to the initialisation of the weights and the randomness of the training. Therefore, we have trained two of our models 10 times with the same hyper-parameters, namely our baseline model, with a VGG backbone, which combines the 4 reconstruction loss components without batch norm and the LSGAN model with batch norm. The results are shown in Table 1, where we show for each performance measure the minimum, the maximum and the average value, and include the standard deviation. We observe some small differences in performance, e.g. ARD in range 0.141 – 0.143 and \(\delta < 1.25\) in the range 0.806 – 0.811. We conclude that minor differences in performance between models, might in fact be the result of initialisation rather than model design and training choices.

In the second experiment in this section, we study the influence of the backbone network used. We compare the VGG30 network, used in all other experiments, to variants of a ResNet backbone, using the full reconstruction loss definition (i.e. L1, LR, disparity & SSIM), without any adversarial components. The results are shown in Table 2. We conclude that the ResNet50 architecture yields best performance on the test set and while the shallow ResNet18 is outperformed by the VGG architecture, it is only by relatively little. This is in line of expectations, since residual learning has been shown to be effective for deep convolutional architectures (He et al., 2016). For the other experiments, however, we use the VGG30 backbone for fair comparison to related work.

4.2. Loss components & GANs

To address our main research question we have performed an extensive set of experiments using different combinations of loss components paired with three different GAN variants. We compare the performance of the model when using different configurations of loss components: L1 Loss, adding Left-Right consistency, adding disparity smoothness, and adding the SSIM loss. For each of the loss component configurations, we also compare the performance of the model without using a GAN, against using a Vanilla GAN, LSGAN or WGAN-GP. The results are shown in Table 3, we refer to experiment indices in parentheses. From the results we observe the following:

\(^1\) Available at https://github.com/rikgroen/depthgan.
Table 3

Performance of models using different loss configurations and GAN variants. The best results for each loss configuration are indicated by blue highlighting, the overall best results have been boldfaced. Model configuration 4.a is our implementation of Godard et al. (2017). We conclude that with the most constraint image reconstruction loss adversarial training does not improve depth estimation, see text for discussion.

<table>
<thead>
<tr>
<th>Loss Components</th>
<th>BN</th>
<th>GAN</th>
<th>ARD</th>
<th>SRD</th>
<th>RMSE</th>
<th>RMSE log</th>
<th>δ &lt; 1.25</th>
<th>δ &lt; 1.25</th>
<th>δ &lt; 1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 LR Disp SSIM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Vanilla</td>
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<td>12.442</td>
<td>18.245</td>
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<td>0.008</td>
<td>0.020</td>
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<td>18.816</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
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<td></td>
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<td>0.766</td>
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<td>✓</td>
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<tr>
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<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>-</td>
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<td>1.049</td>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>1.357</td>
<td>6.003</td>
<td>0.249</td>
</tr>
</tbody>
</table>

Training set mean

0.361 4.826 8.102 0.377 0.638 0.804 0.894

Table 4

The effects of different kinds of normalisation on the performance of depth prediction (in ARD) using Vanilla or LSGAN adversarial training. We evaluate no-normalisation (-), instance normalisation (IN), and batch normalisation (BN). We conclude that BN is important for obtaining good results.

<table>
<thead>
<tr>
<th>GAN</th>
<th>L1</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IN</td>
<td>BN</td>
</tr>
<tr>
<td>Vanilla</td>
<td>0.215</td>
<td>0.208</td>
</tr>
<tr>
<td>LSGAN</td>
<td>0.216</td>
<td>0.183</td>
</tr>
</tbody>
</table>

Fig. 2. Error scatter plots of the Absolute Relative Distance (ARD, lower is better) for each image, comparing models with and without GAN loss: (i) the left plot shows a L1 loss model with BN (entry in 3.t 2.b) against a L1 loss WGAN (2.e); (ii) right plot shows a full loss model with BN (4.b) against a full component LSGAN with BN (4.d); The diagonal indicates equal performance for both model. E.g. in (i) the blue dots represent those images for which a L1 loss with BN outperforms the L1 loss complemented with WGAN. Note the different scaling between plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Batch & instance normalisation. In this experiment we evaluate the influence of normalisation strategies on the performance. We compare the L1 and the full reconstruction loss, trained without GAN or with Vanilla/LSGAN. The results are shown in Table 4. From the results, we observe that for any configuration of loss components, performance improves when batch normalisation is used. While instance normalisation does not yield better performance for a full loss model, it is beneficial for models trained with a L1 loss. We conclude that batch normalisation is important for training for any model. Qualitative investigations in Fig. 5 show that batch normalisation takes away some granularity in the predicted disparities.
4.3. Reconstructed image quality & GANs

In the previous section we quantitatively show how performance of models is affected making use of adversarial losses. GANs optimise for photo-realism in reconstructed images, which could lead to well-reconstructed images while the predicted disparities poorly model accurate depth. This is because many disparity maps may reconstruct an image well even though they do not capture depth correctly. We evaluate the performance of the non-adversarial model versus GANs at the level of individual images to see if there are cases for which GANs are better suited. The results are presented in Fig. 2. When using only the L1 reconstruction loss (left plane), the variance in the performance difference between models trained with and without GANs is large (i.e. many outliers away from the diagonal). However, when using...
<table>
<thead>
<tr>
<th>L1 loss</th>
<th>Full loss</th>
</tr>
</thead>
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<tr>
<td><strong>Input</strong></td>
<td><strong>Input</strong></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VGAN</strong></td>
<td><strong>VGAN</strong></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LSGAN</strong></td>
<td><strong>LSGAN</strong></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WGAN</strong></td>
<td><strong>WGAN</strong></td>
</tr>
</tbody>
</table>

Fig. 4. Comparison of the three different GAN variants: Vanilla GAN, LSGAN and WGAN, compared for both models trained with only L1 loss (top) and models trained with the full loss (bottom). For each of the image blocks, the top row shows input images $I$ to the generator. Then for each GAN variant we show the reconstructed left images $\hat{I}$ and the right-to-left disparities $d$. Not especially that WGAN severely smooths disparity predictions when paired with only a L1 loss. This effect is much less pronounced when it is paired with our full loss. Compared with the Vanilla GAN and LSGAN, the WGAN recognises objects in the foreground to a lesser extent (see the second column on the left). Best viewed in colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the full reconstruction loss, the scatter is aligned around the diagonal, indicating that both models perform similarly on most images. We have verified the few outliers visually, but do not find a noticeable patterns which indicates better photo-realism for GANs in these cases.

In Fig. 3 the reconstructed images and their corresponding disparities are shown for L1, WGAN L1, Full and Full WGAN models. The model trained using only a L1 loss can reconstruct images that have a low pixel-wise loss, but impose no structure on the disparities. This means that there are holes and strong transitions in the predicted disparities. For the WGAN that was trained alongside a L1 loss, it seems the WGANs prefers to predict low disparities. This way images that are very close to the input image are generated. As such, even though the disparities are poor, the reconstructed images are photo-realistic. Adding more geometric loss components that constrain the disparities alleviates these problems.

We also visually compare the performance of different GAN variants in Fig. 4 for models that were trained alongside a L1 loss and a full loss. Again, for models trained with a L1 loss, it can be seen that the WGAN predicts low disparities compared to the other GAN variants. This is beneficial for depth estimation, since it smooths the disparities...
and prevents under-estimating depth. In a way, the WGAN trained alongside the L1 loss imitates the disparity smoothness loss component. This effect is much less pronounced for models trained with a full loss.

In a next experiment we compare the image quality (rather than the depth prediction quality) of the reconstructed images, measured by L1, L2, and SSIM scores on the test set. The results are shown in Table 5. The first row shows the identity mapping, indicating the scores comparing left and right ground truth images directly. In the rest of the table we can see that there are subtle differences between methods in image space. WGAN reconstruction is marginally worse than other methods. The results are interesting, because it seems image reconstruction score has relatively low correlation with depth estimation scores, the image quality of the L1 based models is higher than the full loss, yet the depth prediction is worse. This implies that there is a need for geometrically founded loss functions, like left–right consistency and disparity smoothness losses to obtain better depth predictions.

### 4.4. Output scales

In this set of experiments, we vary the number of output disparity predictions from 4 (as used in Godard et al. (2017)) to 1 (as used in Pilzer et al. (2018)). We do so for two settings of the reconstruction loss, using only L1 + LR loss, similar to Pilzer et al. (2018) and using the full reconstruction loss, similar to Godard et al. (2017). The results are shown in Table 6, using the ARD performance measure. From the results we observe that reducing disparity output scales contributes positively to depth estimation quality, this holds especially in the case of using just the L1 + LR loss. The intuition is that forcing the network to output coherent disparities early on can over-regularise disparities: With 4 output scales the smallest resolution of disparities is just $32 \times 64$, which acts as a (too) strict regulariser.

### 4.5. Generalising from KITTI to CityScapes

In this set of experiments we evaluate our models on the CityScapes dataset, after training on the KITTI dataset. The goal is to see if the insights and results generalise to this novel domain. Results are depicted in Table 7. The results indicate similar behaviour on the CityScapes dataset as on the KITTI dataset: when the reconstruction losses are sufficiently constrained, adversarial training does not improve the performance. We obtain the best generalising results by using a combination of all four image reconstruction losses, trained at a single scale, using batch normalisation.

### 4.6. Comparison to state-of-the-art

In the final set of experiments, we compare the performance of our current work to a few state-of-the-art methods on KITTI, see Table 8. For comparison, we report performance on the Eigen test set, using centre cropping (Garg et al., 2016). For reference we include a few seminal works on monocular depth estimation, when using the LiDAR data during training (Saxena et al., 2006; Eigen et al., 2014) and one of the newest methods (Yang et al., 2018). Then we compare our performance to the work of Godard et al. (2017, 2018), and Pilzer et al. (2018), since these serve as baselines.
and inspiration for the current work. While adding adversarial losses to take into account scene context does not improve over a combination of reconstruction based lasses, using batch normalisation and just 2 output scales significantly boost performance.

5. Conclusions

This work has sought to investigate whether using adversarial losses benefits the estimation of depth maps in a monocular setting. For many tasks in which global consistency is important, adversarial training improves image reconstruction tasks. However, after extensive experimental evaluation, we conclude that adversarial training is beneficial in tasks in which global consistency is important, adversarial training contributes hardly to the quality of the predicted depth maps and may even be harmful.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.cviu.2019.102848.

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Godard, C., Mac Aodha, O., Firman, M., Brostow, G.J., 2017. Unsupervised monocular depth estimation with left-right consistency. In: CVPR.
