

Halluci-Net: Scene Completion by Exploiting Object Co-occurrence Relationships

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Abstract

Recently, there has been substantial progress in image synthesis from semantic labelmaps. However, methods used for this task assume the availability of complete and unambiguous labelmaps, with instance boundaries of objects, and class labels for each pixel. This reliance on heavily annotated inputs restricts the application of image synthesis techniques to real-world applications, especially under uncertainty due to weather, occlusion, or noise. On the other hand, algorithms that can synthesize images from sparse labelmaps or sketches are highly desirable as tools that can guide content creators and artists to quickly generate scenes by simply specifying locations of a few objects. In this paper, we address the problem of complex scene completion from sparse labelmaps. Under this setting, very few details about the scene (30% of object instances) are available as input for image synthesis. We propose a two-stage deep network based method, called ‘Halluci-Net’, that learns co-occurrence relationships between objects in scenes, and then exploits these relationships to produce a dense and complete labelmap. The generated dense labelmap can then be used as input by state-of-the-art image synthesis techniques like pix2pixHD to obtain the final image. The proposed method is evaluated on the Cityscapes dataset and it outperforms two baselines methods on performance metrics like Fréchet Inception Distance (FID), semantic segmentation accuracy, and similarity in object co-occurrences. We also show qualitative results on a subset of ADE20K dataset that contains bedroom images.

1. Introduction

Reconstruction of scenes has been a project that humankind has undertaken since pre-historic times. While democratization of cameras has exponentially improved our ability to capture images, recently there has been a growing body of work on synthesizing images from labelmaps.

*This work was done while Kuldeep and Tejas were at CMU.

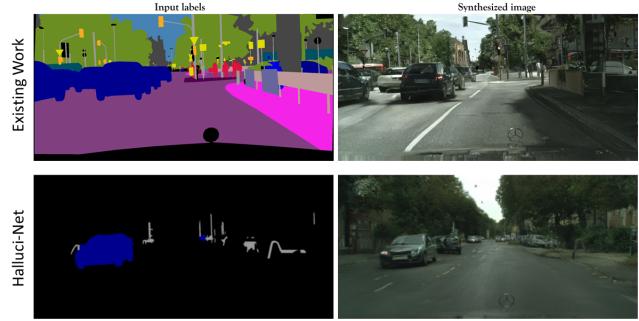


Figure 1. This paper addresses the task of image synthesis from sparse labelmaps, in contrast to existing work which assumes complete labelmaps as inputs. This work is a step towards image synthesis models that can hallucinate the complete scene when sparse and incomplete inputs are encountered.

Image synthesis techniques, powered by generative models [6], have led the progress of converting high-level inputs to images, such as for synthesizing images from labels [9, 22, 17] or for converting sketches to images [1, 21], by designing an image-to-image translation framework using conditional GANs. However, complex scenes like streets and bedrooms are often composed of several objects that require very precise pixel-level information in the form of dense labelmaps or sketches. While fully-supervised methods such as pix2pixHD [22], GauGAN [17] are able to generate high-quality photorealistic images from dense labelmaps, they do not possess the ability to do so when only partial labelmaps are available.

In many cases, a complete labelmap of a scene is not available, but partial information such as locations of some objects may be available. Humans (or rather, some artistic humans [2]) are able to imagine and recreate scenes from partial memory. However artists need to spend prohibitively large amounts of time at creating scenes using conventional art media such as paints, watercolor, ink or charcoal. It is therefore highly desirable to empower them with the ability to create images of new scenes with desired characteristics and constituent objects, while minimizing the amount of ef-

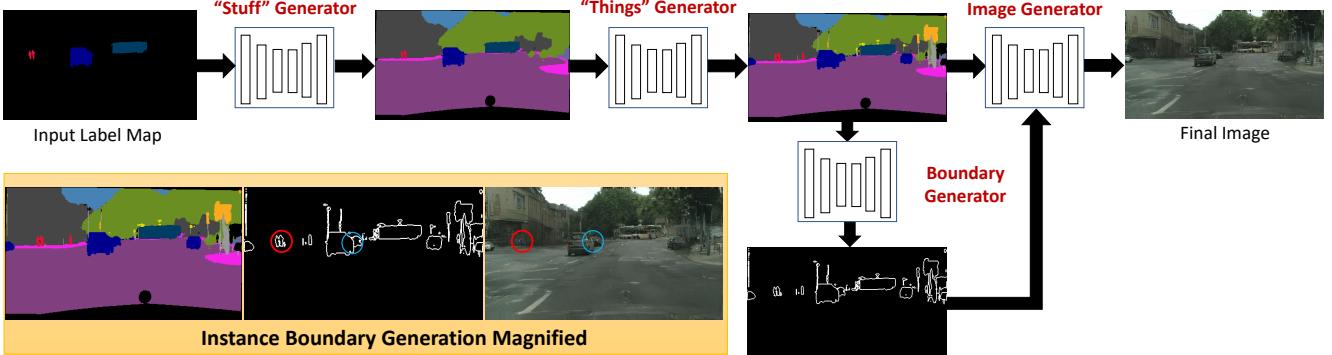


Figure 2. Overview of the algorithm: for both stages, we train a GAN using a modified pix2pix based generator. Inset shows details of generated instance boundary maps. The instance boundaries created between adjacent cars and adjacent persons are in blue and red circles respectively. Boundary maps help create distinguishable instances of the same object class in the synthesized images.

fort needed. An image synthesis technique (as shown in Figure 1) that can receive an input with only a few known object locations and classes, and generate the image for the complete scene, is a step towards this goal.

This paper addresses this problem of scene completion from sparse labelmaps or labelled sketches. Under this setting, the complete labelmap is not available, but the locations of only some of object instances are available as shown in Figure 1. While existing work in image synthesis from sparse sketches [1, 5] only deals with single objects such as shoes or handbags, our work can handle complex scenes with multiple objects and layouts.

To generate the entire scene, one must first learn to speculate about the complete labelmap, i.e. the locations and class labels of other object instances. We divide this problem into several stages as shown in Figure 2. The first stage takes sparse labelmaps as input, and generates a labelmap for the so-called “stuffs” classes (such as road, sidewalk, sky) which provide global scene context. The second stage then uses both the sparse labelmap and the stuffs labelmap to generate a labelmap for the so-called “things” class, that contains fine-grained object classes such as pedestrians, cars, and traffic signs. We then generate instance boundaries for the “things” class. These instance boundaries and the hallucinated labelmap are then utilized for synthesizing a high-resolution RGB image. Halluci-Net therefore first learns object co-occurrence relationships, and exploits them to convert a sparse labelmap to a complete labelmap and instance boundaries, followed by image synthesis.

The contributions of this paper are summarized below:

- We introduce a new problem of complex scene completion from extremely sparse inputs such as labelmaps or labelled sketches.
- We propose a two-stage method, ‘Halluci-Net’ that captures the object co-occurrence relationships to generate dense labelmaps.
- We propose a method to create object instance bound-

ary maps from semantic labelmaps, that are utilized to generate images with well-defined boundaries between different instances of the same object class.

- Our two-stage method beats the baseline single-stage method by a considerable margin on various metrics like FID, semantic segmentation measures, similarity in object co-occurrence metrics and human preference scores, and the direct labelmap to image (zero-stage) method in terms of FID.

2. Related Work

Generative Adversarial Networks (GANs) have been used to generate images using random inputs seeds [19]. In order to learn the distribution of images, GANs employ two competing networks – a generator that outputs a synthesized image, and a discriminator that predicts whether an image is from the dataset or is synthesized. GANs have been used for numerous vision tasks such as image editing [27], image inpainting [23], and super-resolution [12].

Conditional GANs (cGANs) [16] have proved to be useful in the task of image-to-image translation, such as generating masked regions of an image [18], high-resolution face images [10], and text-to-images synthesis [24]. pix2pix [9] presents cGANs as a generic solution for numerous image-to-image translation tasks, such as generating images from labelmaps, objects from edge maps, image colorization, thermal images to color images, maps to aerial photos, and day-time images to night-time images. pix2pixHD [22] improves upon pix2pix by generating high resolution (2048X1024) and visually appealing images. It incorporates information regarding object instances (in addition to semantic labelmaps) so as to create well-defined boundaries between object instances of the same category. However, the pix2pixHD architecture is prone to producing similar results for different object categories if the input labelmap is too homogeneous. Park *et al.* [17] overcome these short-

comings by introducing the spatially-adaptive conditional normalization (SPADE). Hong *et al.* [8] propose a method to manipulate an image with addition and deletion of objects, given the locations and object categories to be manipulated. Liu *et al.* [15] propose a generator predicts convolutional kernels conditioned on the semantic labelmap, and a discriminator that enhances the semantic alignments between generated images and labelmaps, as compared to the multi-scale discriminator used in pix2pixHD.

Sketch-to-Image Generation: SketchyGAN [1] and ContextualGAN address the problem of generating images from hand-drawn sketches. This problem considered to be harder than generating images from edges because of the pixel-wise misalignment between sketches and images. However this work deals only with iconic images with single objects (such as faces, birds, cars, shoes, and handbags). More recently GAN-based sketch-to-image methods have been extended to the more diverse COCO dataset [4]. We seek to solve an even harder problem of image synthesis from sparse labelmaps, i.e. when very few pixels are annotated with labels, which requires learning co-occurrence of objects to hallucinate the entire scene.

3. Object Co-occurrence Networks

We propose a two-stage approach – “Halluci-Net” to generate dense labelmaps from sparse labelmaps.

3.1. Baseline Methods

Before we discuss our two-stage method, we present two baselines for comparison: zero-stage and single-stage.

Zero Stage: Sparse map \rightarrow Image

Single Stage: Sparse map \rightarrow Dense map \rightarrow Image

Zero-stage baseline method: The zero-stage method consists of a single generative adversarial network that directly maps the sparse input labelmap of size $C \times H \times W$ (where C is the number of classes, H and W are the height and width of the labelmap respectively) to image space. The generator architecture is same as pix2pixHD [22] and it is trained with loss functions similar to the pix2pixHD. This method yields reasonable quality images, but falls short of producing new objects, especially the ‘things’ classes.

Single-stage baseline method: To overcome this limitation, we train a GAN with generator G_{single} conditioned on the sparse labelmap of size $C \times H \times W$, where C, H, W are the number of classes, height and width of the labelmap respectively. The input label $s(c, x, y)$ equals 1, if the pixel at (x, y) belongs to class c , otherwise it is zero. The generator architecture is similar to U-Net [20], except for the first layer, wherein the number of input channels is given by the number of classes. The output of the generator is a dense

labelmap $g(c, x, y)$ of size $C \times H \times W$, the same size as the input. We use a sigmoid function as the last layer to enforce $g(c, x, y) \in [0, 1]$. We use a multi-scale discriminator with a least-square adversarial loss, similar to pix2pixHD.

3.2. Halluci-Net: Two-stage method

First, we divide the class labels into two categories:

1. *stuffs*: background entities such as road, building, tree, sky, ...
2. *things*: foreground objects like car, person, bike, ...

Our input sparse labelmap consists only of “things”.

Our proposed two-stage method consists of two generative adversarial networks. The first stage generator – G_1 , takes a sparse labelmap of size $(C_{things} + 1) \times H \times W$, and generates the “stuffs” labelmap of $C_{stuff} \times H \times W$, i.e. predicts pixel locations corresponding to various stuff classes. We use the U-net architecture [20] for G_1 and train it with an adversarial loss conditioned on the sparse labelmap.

We overlay the output of the first stage network with the input sparse labelmap and feed it to the second stage generator G_2 . This stage has an architecture similar to G_1 except for the number of the channels in the input and output. The input of this generator is the overlayed labelmap of size $C \times H \times W$. The output of the second stage generator consists of “things” class labelmap of size $C_{things} + 1 \times H \times W$, where C_{things} is the number of “things” classes. We then overlay the second stage input and the second stage output to get the final dense map of size $C \times H \times W$. The first and the second stage generators are trained independently. As in the single-stage method, we use the multi-scale discriminator with a least-square adversarial loss.

Loss functions: For both the baseline and two-stage method, we use the object co-occurrence loss, L_{OC} in (1) to train the generator. Given the generated labelmap g^* and the ground-truth labelmap g , L_{OC} consists of a standard adversarial loss L_{adv} , focal loss L_{FL} (Equation 3), and a discriminator feature loss L_{FM} similar to pix2pixHD [22].

$$L_{OC} = L_{adv}(g^*, g) + \lambda_{FL} L_{FL}(g^*, g) + \lambda_f L_{FM}(g^*, g) \quad (1)$$

In semantic segmentation tasks, cross-entropy loss function is typically used for the labelmaps. However since it did not achieve desirable results for our task, we use the focal loss:

$$L_{FL}(g^*, g) = \sum_{x,y,c} l_{FL}(g^*(c, x, y), g(c, x, y)), \text{ where } (2)$$

$$l_{FL}(p, y) = -y(1-p)^\gamma \log p - (1-y)p^\gamma \log(1-p). \quad (3)$$

Focal loss has been shown to help in the detection of hard-to-classify objects in presence of a large number of easy-to-classify objects [14]. In our case, it helps in generating rare or hard-to-generate classes like “biker” and “vegetation” in presence of common or easy-to-generate classes like “road”, “tree”, “side-walk”, etc.

4. Instance Boundary Generation

While the proposed two-stage approach can generate plausible dense labelmaps, the nature of the output does not allow us to differentiate between different instances of the same object category. In other words, a blob of pixels indicated as belonging to a certain object category may actually consist of pixels of multiple instances of the same category. This can be seen in Figure 2 where, in the labelmap, there are blobs of “car” and “person” categories large enough to consist of multiple instances. Wang *et al.* [22] show that when labelmaps with such a characteristic are fed into image generators like pix2pixHD, the boundary between two objects of the same class in the image generated is unclear and the objects generated tend to merge into each other. Hence, such blobs need to ‘split’ to create multiple instances and the instance information needs to be incorporated to generate well-defined boundaries in the image. Wang *et al.* [22] also propose to use instance boundary maps as a proxy for incorporating instance information to synthesize images with well-defined boundaries between instances of the same object category. To produce such instance boundary maps, they use the ground-truth instance map information, where a pixel is assigned as a boundary pixel if at least one of its four neighbors has a different instance ID.

However, in our case, since the inputs to the image generators are “hallucinated” labelmaps (generated from sparse labelmaps), we do not have access to instance IDs. To circumvent this, we train a GAN to map labelmaps to the corresponding instance boundary maps without ever creating the instance IDs. The ground truth to train the instance boundary maps is readily available from the instance ID maps in the dataset. The generator architecture is the same as U-Net, except for a two-channel output and the first layer that reflects the size of the input label. To train the generator for the instance boundary map, we use the loss function, L_{bd} similar to Equation 1, given below:

$$L_{bd}(b^*, b) = \lambda_{FL} L_{FL}(b^*, b) + \lambda_{FM} L_{FM}(b^*, b) + L_{adv}(b^*, b) + \lambda_{VGG} L_{VGG}(b^*, b) \quad (4)$$

L_{adv} is the standard adversarial loss, $L_{FL}(b^*, b)$ is the focal loss between the generated boundary map, $b^* = G_{bd}(g^*)$ and the ground-truth $b = G_{bd}(g)$. We also add VGG feature loss, L_{VGG} for the boundary maps by replicating the boundary maps thrice to form a 3-channel input to compute VGG loss, similar to Wang *et al.* [22].

Figure 2 shows the labelmaps and the corresponding instance boundary maps generated by our network. The large blob corresponding to the car is split by our network into multiple instances by creating boundaries (marked by blue circle), and similarly the blob of “person” class is split into multiple instances (marked by a red circle).

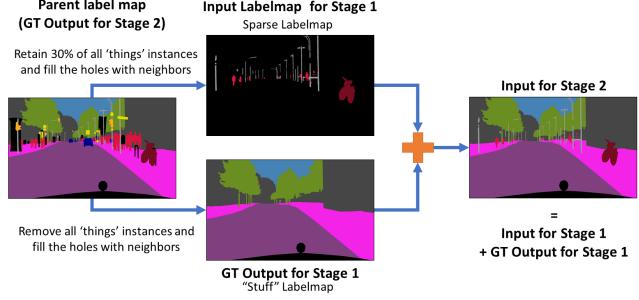


Figure 3. This dataset creation pipeline shows the creation of input-output pairs from existing datasets for training Halluci-Net.

5. Experiments

We evaluate our approach to scene completion on the two datasets: Cityscapes [3] and ADE20K [26]. The Cityscapes dataset consists of 2975 examples in the training set and 500 examples in the validation set. The object classes in this dataset, as mentioned earlier can be divided into two categories, “things” like cars, biker, person etc., and “stuff” like trees, road, side-walk etc. In ADE20K dataset, we consider only bedroom scene images for our experiments. This bedroom scene set consists of 1389 examples for training and 139 examples for validation. The ADE20K dataset consists of very large number of object classes but we consider only top-30 object classes (based on the frequency of occurrence per image) and we group the rest into a single class. Similar to Cityscapes dataset, we also divide the ADE20K dataset object classes into two categories, “things” like bed, table, lamp etc., and “stuff” like wall, floor, ceiling etc. However, these datasets provide dense labelmap and image pairs, instead of sparse labelmaps inputs required for our experiments. To this end, we create our own train/validation datasets to evaluate our approach to scene completion.

5.1. Dataset Preparation

There is no dataset that is readily available to train the two stages of ‘Halluci-Net’. We first need sufficiently large number of (*sparse labelmap, dense labelmap*) pairs. The Cityscapes and the ADE20K datasets were primarily released for the task of semantic segmentation, and contain pixel-wise labelmaps, instance ID maps and the corresponding images. We observe the average number of object instances per training example across the dataset is ~ 32 in Cityscapes and ~ 31 in ADE20K. Given a parent dense labelmap in the original dataset, we first remove all pixels belonging to “stuff” categories and retain 30% random object instances from “things” categories. Thus, it is possible to create a large number of sparse labelmaps, for every parent dense labelmap, by randomly sampling 30% “things” in each image. Each sparse labelmap and corresponding dense labelmap forms the expected input-output pair for our approach. In Figure 3, we illustrate our data creation pipeline.

Method	Zero-Stage	Single-Stage	Halluci-Net
w/o inst-bd	46.21	44.74	41.19
with inst-bd	-	42.05	40.67

Table 1. Comparison of FID scores (lower \Rightarrow better) with and without instance boundary on Cityscapes [3]. Halluci-Net with inst-bd is the best, while Halluci-Net w/o inst-bd also performs considerably better than the single stage approaches.

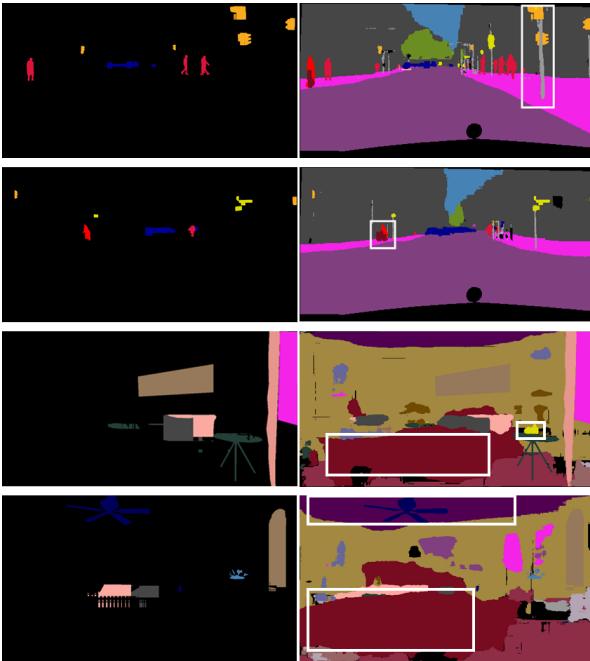


Figure 4. Illustration of our method’s ability to capture object co-occurrence relationships. Row 1: Poles are produced next to traffic-sign (yellow) and traffic-light (orange); Row 2: Bikes are produced adjacent to bikers; Row 3, 4: bed (red) is produced adjacent to pillow (pink); ceiling is produced next to fan (blue) and top of bed. Row 4: clock (yellow) is generated on top of table (green).

5.2. Training

We train all the networks for 200 epochs. In each epoch, for a parent dense labelmap in the original dataset, we use a different set of randomly chosen 30% “things” categories, and remove all “stuff” classes. We fix the resolution to 512×256 for Cityscapes and 512×384 for ADE20K. We use Adam optimizer [11] with $\beta_1 = 0.5$, $\beta_2 = 0.999$, learning rate of 0.001 with linear decay after 100 epochs. λ_f and λ_{VGG} (if used) are set to 10, and λ_{fl}, γ to 5 for all experiments. The instance boundary network is also trained with the same set of hyper-parameters.

5.3. Quantitative performance

We evaluate performance of our methods using four metrics, namely Fréchet Inception distance (FID), similarity in object co-occurrence statistics, semantic segmentation and a human evaluation study.

Fréchet Inception Distance (FID)[7] is a standard metric used to quantify the fidelity of images generated by GANs. FID measures the distance between the distribution of the generated images and the real images in a feature space. A pre-trained inception network is used to extract the features corresponding to each image and the mean and covariance of real and generated features m_r, C_r, m_g, C_g respectively are computed. Then the FID score is calculated as:

$$FID = \|m_r - m_g\|_2^2 + Tr(C_r + C_g - 2(C_r C_g)^{\frac{1}{2}}) \quad (5)$$

Table 1 shows the FID scores for Halluci-Net for the Cityscapes dataset, in comparison with the zero-stage and single-stage baselines with and without instance boundary, with lower FID score implying superior performance. Among all approaches, Halluci-Net with instance-boundaries yields the lowest FID score of 40.67. Halluci-Net without instance-boundaries also performs considerably better than the single stage approaches. While the direct method yields a FID score of 46.21, it gets progressively better for the single-stage and the proposed Halluci-Net method. On ADE20K dataset, Halluci-Net with instance-boundaries has the best FID score of 174.89 while the single-stage method yields a score of 189.31.

Similarity in object co-occurrence: In order to evaluate the ability of our method to incorporate object co-occurrence in the output, we use the similarity measure proposed by Li et. al [13]. Let $N(c_1)$ be the number of examples in the input dataset in which there is at least one instance of class c_1 . For the corresponding outputs, let $N(c_1, c_2)$ be the number of examples for which there is at least one instance of class c_2 , that was not present in the input, Then we can compute the probability of co-occurrence for c_2 , given c_1 and the similarity in co-occurrence as:

$$P_{oc}(c_2|c_1) = \frac{N(c_1, c_2)}{N(c_1)} \quad (6)$$

$$sim_{oc}(c_1|c_2) = 1 - |P_{oc}^{train}(c_1|c_2) - P_{oc}^{gen}(c_1|c_2)|. \quad (7)$$

Table 2 shows the similarities in co-occurrences for different pairs of input and output target classes for Cityscapes. A score closer to 1 implies high similarity in object co-occurrences between generated and training dataset.

Figure 4 shows a qualitative analysis of object occurrences captured by our approach in the final output, for Cityscapes as well as ADE20K datasets. In columns 1 and 2, given that there was a biker in the input, our method is able to appropriately guess the presence and the location of the bike (shown inside the white box). Similarly traffic lights are produced at appropriate locations and shape conditioned on the locations of the poles in the input. In the bedroom scenes in columns 3 and 4, beds are produced under pillows, ceiling near the fan, and a clock on top of

Method	(Car, Parking)	(Person, Person)	(Pole, Building)	(Bicycle, Rider)	(Person, Sidewalk)	(Car, Bus)
Halluci-Net	0.97	0.93	0.89	0.71	0.95	0.93
Single Stage	0.84	0.92	0.54	0.53	0.96	0.80

Table 2. The table shows similarity between the training and generated sets in terms of object co-occurrences for various pairs of input and output object classes on the Cityscapes [3]

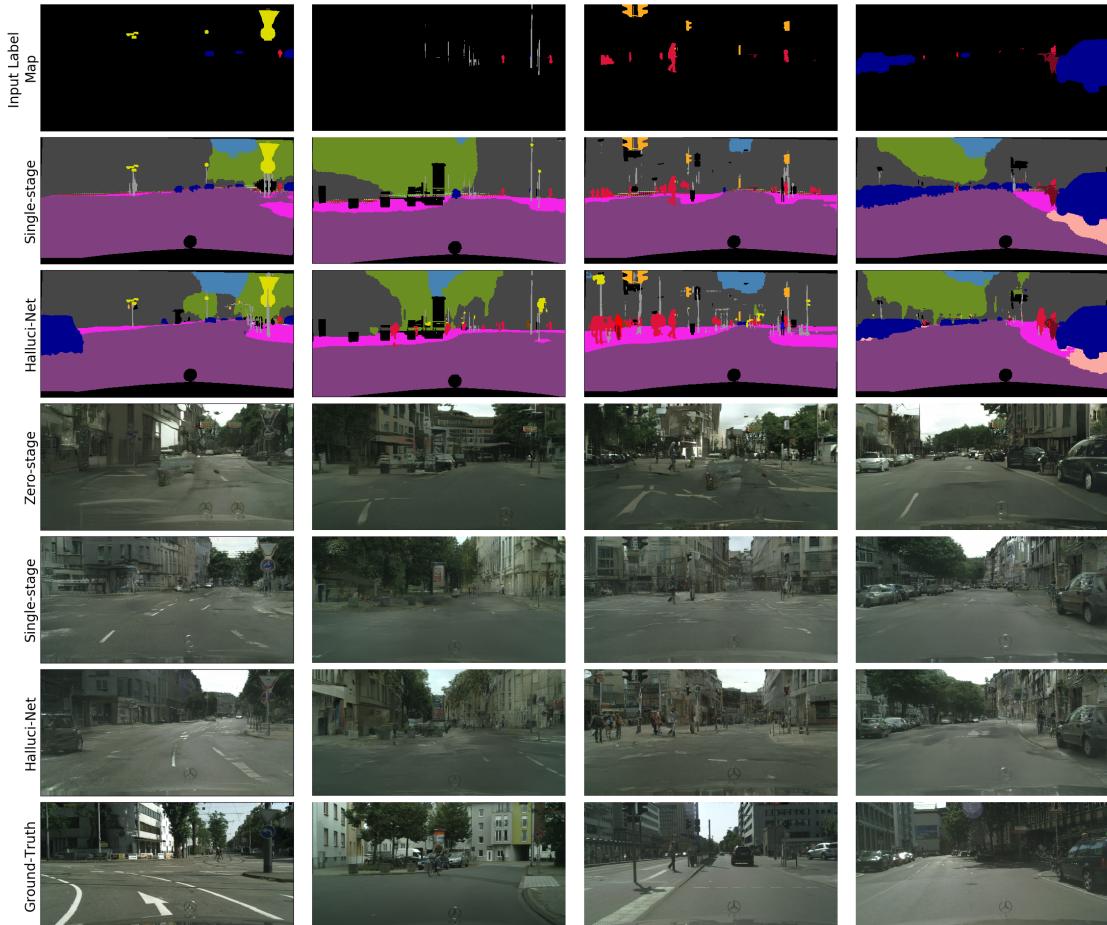


Figure 5. Comparison of dense labelmap outputs produced by the two methods. As can be seen, the two-stage method produces more details and smoother object shapes. The single-stage method is also prone to producing artifacts. Once the dense labelmap is produced, the corresponding image is generated using pix2pixHD. For comparison, we show the ground truth image in the last row.

a table. This evidence suggests that our method is able to capture the inherent object co-occurrence relationships.

Semantic Segmentation Score: To evaluate the utility and quality of the generated labelmaps and generated images, we train a semantic segmentation network [25] (with ResNet50 as the backbone) using the generated pairs, and test on the original validation set of images. Halluci-Net performs better than the Single-Stage baseline in terms of all standard semantic segmentation metrics as shown in Table 4. For comparison, we show the results using the Oracle PSPNet, that is trained on the original labelmap–image pairs. We also show the mIoU accuracies

for different object categories in Table 3. It can be seen that the Halluci-Net+PSPNet performs better than Single-Stage+PSPNet for most object categories, except “train”. However, for classes like train, motorcycle, wall and fence, the proposed method performs poorly as compared to the Oracle PSPNet. This shows the limitation of our method to generate less-frequent object categories.

Human Evaluation Study: In addition to this, we perform a human evaluation study on the generated labelmaps from our method and the baseline method. We show 200 randomly selected pairs of labelmaps to five human workers, and asked them to tell which of the two labelmaps they

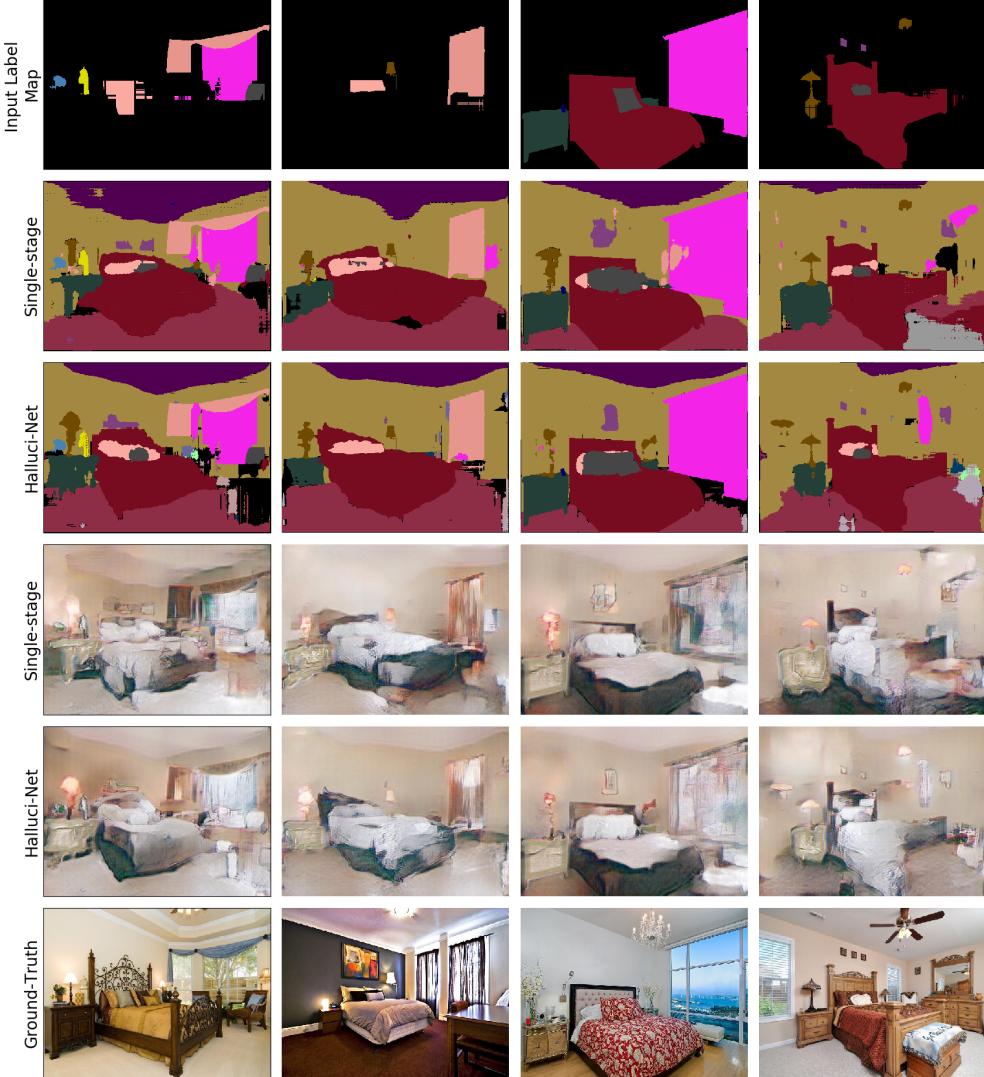


Figure 6. The figure shows the comparison of dense labelmap outputs from the single-stage baseline method and the proposed two-stage method on ADE20K dataset [26]. As can be seen, the two-stage method produces plausible scene layouts.

Class	road	side-walk	building	pole	traffic-light	traffic-sign	motorcycle	train	bus	wall	fence
Single-Stage+PSPNet	0.9600	0.6955	0.8472	0.4418	0.4911	0.5913	0.3228	0.2496	0.3845	0.0811	0.1272
Halluci-Net+PSPNet	0.9657	0.7400	0.8534	0.4719	0.4906	0.5947	0.3228	0.2249	0.4050	0.1309	0.2948
Oracle PSPNet	0.9801	0.8414	0.9222	0.6399	0.7078	0.7826	0.7764	0.7219	0.8815	0.5208	0.5968

Table 3. Segmentation scores (mIoU) on Cityscapes dataset [3] for different object categories. Halluci-Net performs better than the single stage approach in most cases.

prefer in terms of shape of the objects that are generated, how much physical sense they make. Across the five human workers, our method was preferred 116 times and the baseline method 84 times.

5.4. Visual Results

We show visual results for scene layout synthesis as well as for image synthesis by comparing Halluci-Net with the

two baseline methods: zero-stage (direct mapping from the sparse label to image) and single-stage method. Results for the Cityscapes dataset are shown in Figure 5. Row 1 shows the input labelmap. It can be seen from row 2 and row 3 that our method produces scene layouts with more details and smoother and precise object shapes, as compared to the baseline method. In rows 4, 5 and 6, we show the images generated for direct method, Single-Stage+pix2pixHD

Method	mIoU	mAcc	Accuracy
Single-Stage+PSPNet	0.5111	0.6215	0.9131
Halluci-Net+PSPNet	0.5501	0.6647	0.9214
Oracle PSPNet	0.7730	0.8431	0.9597

Table 4. Segmentation scores in terms of mean Intersection over Union (mIoU) and per-pixel accuracies on Cityscapes dataset [3] with PSPNet trained on the generated label-image pairs from different methods. The scores are obtained on the label-image pairs from the original validation set.

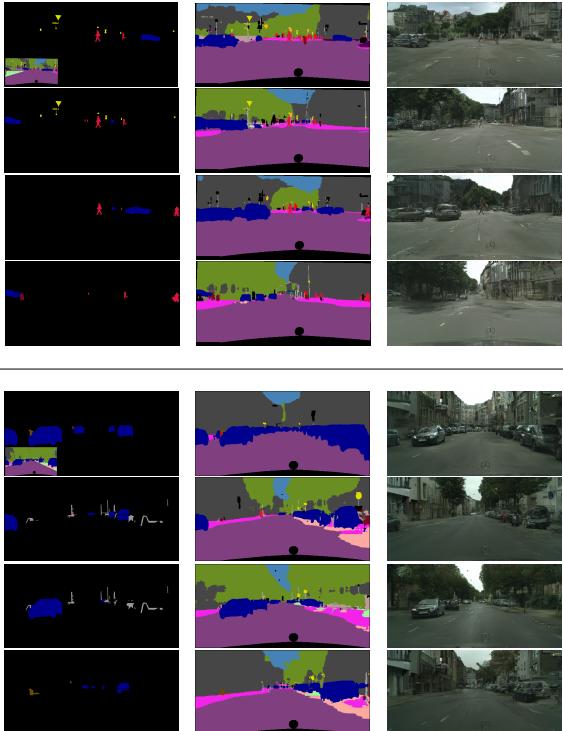


Figure 7. The figure shows how it is possible to generate multiple novel scene layouts, given a parent dense scene layout (inset). Column 1: four different randomly sampled sparse labelmaps. Column 2: different dense labelmaps produced by the proposed method. Column 3: corresponding synthesized image.

and Halluci-Net+pix2pixHD. With sparse inputs, the zero-stage method is prone to produce artifacts in the images that are generated as can be seen in column 1 and 3. As compared to direct method and Single-Stage+pix2pixHD, Halluci-Net+pix2pixHD produces images with richer content owing to the superior scene layout created by the two-stage network. For comparison we have shown the ground-truth expected image. Similarly, in Figure 6, we show the synthesized scene layouts and the corresponding images for the baseline Single-Stage method and the proposed Halluci-Net method on ADE20K dataset. Our method is able to generate plausible scene layouts.

5.5. Single Layout to Multiple Layouts

We propose a method to interactively generate several scene layouts from a single dense layout. In Figure 7 we show how a user can edit a dense scene layout. The user can choose to sample different object instances. Column 1 shows four such random sampling of object instances from the parent scene layout. Column 2 shows the different scene layouts that were generated using Halluci-Net and finally images generated are shown in Column 3. This simple experiment shows the potential of our method to generate novel scene layouts. multiple variants for the complete scene can be synthesized. These algorithmically generated images can be used by content creators directly, or indirectly as templates to guide paintings or drawings on conventional art media.

6. Conclusion

We introduced the new problem of generated complex scenes, composed of several objects from extremely sparse labelmaps and proposed a two-stage network approach to generate the dense labelmap. We show both qualitatively and quantitatively that the proposed method is able to produce high-quality dense labelmaps for street traffic images in Cityscapes dataset and bed-room images in ADE20K dataset. While the results are highly encouraging, we also note that our method is limited in its ability to generate objects of rare classes like wall, fence, as demonstrated earlier in terms of low segmentation accuracy.

Broader Impact

Image synthesis with constraints has broad applications in consumer and industrial applications such as autonomous driving. Application areas in the consumer media realm include image-synthesis for graphics, arts, and social-media. Further, image synthesis is also being currently used to collect training-sets for domains in which data collection may be difficult. In this situation, there is the open question of whether machine-learning techniques trained on synthetic imagery are trustworthy in critical deployments. Image synthesis approaches that can generate very realistic looking pictures can also have unintended effects such as in the spread of disinformation. To mitigate these unintended effects, there is a parallel body of technical work in detecting sources of disinformation in synthesized imagery. Further, there is an implicit reliance on large computational resources, which in turn implies financial resources. Additional avenues of research to investigate the ethical and legal implications of using image-synthesis techniques, and whether they lead to trustworthy systems, should be encouraged with use-inspired interdisciplinary teams.

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References

- [1] Wengling Chen and James Hays. Sketchygan: Towards diverse and realistic sketch to image synthesis. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 9416–9425, 2018. [1](#), [2](#), [3](#)
- [2] Dale J Cohen and Susan Bennett. Why can’t most people draw what they see? *Journal of Experimental Psychology: Human Perception and Performance*, 23(3):609, 1997. [1](#)
- [3] Marius Cordts, Mohamed Omran, Sebastian Ramos, Timo Rehfeld, Markus Enzweiler, Rodrigo Benenson, Uwe Franke, Stefan Roth, and Bernt Schiele. The cityscapes dataset for semantic urban scene understanding. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 3213–3223, 2016. [4](#), [5](#), [6](#), [7](#), [8](#)
- [4] Chengying Gao, Qi Liu, Qi Xu, Limin Wang, Jianzhuang Liu, and Changqing Zou. Sketchycoco: Image generation from freehand scene sketches. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2020. [3](#)
- [5] Arnab Ghosh, Richard Zhang, Puneet K Dokania, Oliver Wang, Alexei A Efros, Philip HS Torr, and Eli Shechtman. Interactive sketch & fill: Multiclass sketch-to-image translation. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pages 1171–1180, 2019. [2](#)
- [6] Ian Goodfellow, Jean Pouget-Abadie, Mehdi Mirza, Bing Xu, David Warde-Farley, Sherjil Ozair, Aaron Courville, and Yoshua Bengio. Generative adversarial nets. In *Advances in neural information processing systems*, pages 2672–2680, 2014. [1](#)
- [7] Martin Heusel, Hubert Ramsauer, Thomas Unterthiner, Bernhard Nessler, and Sepp Hochreiter. Gans trained by a two time-scale update rule converge to a local nash equilibrium. In *Advances in Neural Information Processing Systems*, pages 6626–6637, 2017. [5](#)
- [8] Seunghoon Hong, Xinchen Yan, Thomas S Huang, and Honglak Lee. Learning hierarchical semantic image manipulation through structured representations. In *Advances in Neural Information Processing Systems*, pages 2708–2718, 2018. [3](#)
- [9] Phillip Isola, Jun-Yan Zhu, Tinghui Zhou, and Alexei A Efros. Image-to-image translation with conditional adversarial networks. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 1125–1134, 2017. [1](#), [2](#)
- [10] Tero Karras, Timo Aila, Samuli Laine, and Jaakko Lehtinen. Progressive growing of gans for improved quality, stability, and variation. *arXiv preprint arXiv:1710.10196*, 2017. [2](#)
- [11] Diederik P Kingma and Jimmy Ba. Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980*, 2014. [5](#)
- [12] Christian Ledig, Lucas Theis, Ferenc Huszár, Jose Caballero, Andrew Cunningham, Alejandro Acosta, Andrew Aitken, Alykhan Tejani, Johannes Totz, Zehan Wang, et al. Photo-realistic single image super-resolution using a generative adversarial network. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 4681–4690, 2017. [2](#)
- [13] Manyi Li, Akshay Gadi Patil, Kai Xu, Siddhartha Chaudhuri, Owais Khan, Ariel Shamir, Changhe Tu, Baoquan Chen, Daniel Cohen-Or, and Hao Zhang. Grains: Generative recursive autoencoders for indoor scenes. *ACM Transactions on Graphics (TOG)*, 38(2):1–16, 2019. [5](#)
- [14] Tsung-Yi Lin, Priya Goyal, Ross Girshick, Kaiming He, and Piotr Dollár. Focal loss for dense object detection. In *Proceedings of the IEEE international conference on computer vision*, pages 2980–2988, 2017. [3](#)
- [15] Xihui Liu, Guojun Yin, Jing Shao, Xiaogang Wang, and Hongsheng Li. Learning to predict layout-to-image conditional convolutions for semantic image synthesis. *arXiv preprint arXiv:1910.06809*, 2019. [3](#)
- [16] Mehdi Mirza and Simon Osindero. Conditional generative adversarial nets. *arXiv preprint arXiv:1411.1784*, 2014. [2](#)
- [17] Taesung Park, Ming-Yu Liu, Ting-Chun Wang, and Jun-Yan Zhu. Semantic image synthesis with spatially-adaptive normalization. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 2337–2346, 2019. [1](#), [2](#)
- [18] Deepak Pathak, Philipp Krahenbuhl, Jeff Donahue, Trevor Darrell, and Alexei A Efros. Context encoders: Feature learning by inpainting. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 2536–2544, 2016. [2](#)
- [19] Alec Radford, Luke Metz, and Soumith Chintala. Unsupervised representation learning with deep convolutional generative adversarial networks. *arXiv preprint arXiv:1511.06434*, 2015. [2](#)
- [20] Olaf Ronneberger, Philipp Fischer, and Thomas Brox. U-net: Convolutional networks for biomedical image segmentation. In *International Conference on Medical image computing and computer-assisted intervention*, pages 234–241. Springer, 2015. [3](#)
- [21] Patsorn Sangkloy, Jingwan Lu, Chen Fang, Fisher Yu, and James Hays. Scribbler: Controlling deep image synthesis with sketch and color. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 5400–5409, 2017. [1](#)
- [22] Ting-Chun Wang, Ming-Yu Liu, Jun-Yan Zhu, Andrew Tao, Jan Kautz, and Bryan Catanzaro. High-resolution image synthesis and semantic manipulation with conditional gans. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 8798–8807, 2018. [1](#), [2](#), [3](#), [4](#)
- [23] Raymond A Yeh, Chen Chen, Teck Yian Lim, Alexander G Schwing, Mark Hasegawa-Johnson, and Minh N Do. Semantic image inpainting with deep generative models. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 5485–5493, 2017. [2](#)
- [24] Han Zhang, Tao Xu, Hongsheng Li, Shaoting Zhang, Xiaogang Wang, Xiaolei Huang, and Dimitris N Metaxas. Stack-

- gan: Text to photo-realistic image synthesis with stacked generative adversarial networks. In *Proceedings of the IEEE International Conference on Computer Vision*, pages 5907–5915, 2017. 2
- [25] Hengshuang Zhao, Jianping Shi, Xiaojuan Qi, Xiaogang Wang, and Jiaya Jia. Pyramid scene parsing network. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 2881–2890, 2017. 6
- [26] Bolei Zhou, Hang Zhao, Xavier Puig, Sanja Fidler, Adela Barriuso, and Antonio Torralba. Scene parsing through ade20k dataset. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2017. 4, 7
- [27] Jun-Yan Zhu, Philipp Krähenbühl, Eli Shechtman, and Alexei A Efros. Generative visual manipulation on the natural image manifold. In *European Conference on Computer Vision*, pages 597–613. Springer, 2016. 2