Efficient Fine-tuning of LLM on a Single GPU

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Introduction

In this project, the LLaMA language model is trained and finetuned to the Alpaca Dataset. Various techniques were explored and implemented to reduce memory consumption and fit the model on a single GPU while preserving accuracy. The models employed are LoRA Linear module, Automatic Mixed Precision, gradient accumulation, and gradient checkpointing.

For the dataset, we found that selecting only the initial 200 samples from the 52,000-sample Alpaca set yielded suboptimal results. So, we opted for a more representative approach by randomly selecting 200 samples from the first half of the 52,000-sample dataset for training, reserving the other half for prompt testing. Additionally, we trained the model on a set of 300 samples randomly chosen from the first half of the dataset to assess text generation quality post-finetuning.

The subsequent sections of this report provide an in-depth exploration of the methodologies applied and their profound impact on the training process.

LoRA Linear Module

Modified the original implementation of the LoRA from loralib by Microsoft by removing the implementations for embeddings and convolutional layers and other non-essential features such as fan_in_fan_out and merge_weights. Then, the LoRA linear module was added to the Q and V layers of the LLaMA model with rank 16, alpha 32, and dropout 0.05 to convert the model to the PEFT model. In order to assist in checkpointing, LoRA linear was applied to the Gate, Up, and Down projection layers of the feed-forward network as well. Since the aim was to reduce the trainable parameters, the rank for LoRA linear for the feed-forward network was 2 with alpha = 4 and dropout = 0.05. Then, while training, all the parameters that were not LoRA parameters were frozen.
Adding LoRA to the model reduces the trainable parameters thereby reducing the computational complexity with not so much reduction in accuracy.

As a result, the total number of trainable parameters was reduced from 6750801920 to 11288576, which is a 99.8% reduction in trainable parameters.

Automatic Mixed Precision

In order to reduce the memory consumption during the forward pass of the model, automatic mixed precision is used, which changes the precision of the data based on the operation being performed. The AMP library of PyTorch is used to implement mixed precision in the training loop. AMP library's auto-cast function uses float16 to calculate the model output and then automatically changes to float32 while calculating the loss. Gradscaler is used in addition to auto-cast to prevent the gradients from flushing to zero ("underflowing"). Then backward pass is done on float32 to preserve the accuracy. Mixed precision is useful in reducing the memory consumption during the forward pass of a model as the activations are 16-bit float instead of 32-bit.

Gradient Accumulation

The batch size chosen for training the model is 1. So, every iteration 1 sample from the dataset is trained. Performing a backward pass on every sample not only increases the memory consumption but also increases the computation time. So, gradient accumulation is used. In gradient accumulation, instead of performing a backward pass on every forward pass of a sample, the backward pass is postponed for a certain number of iterations, during which the loss and gradients are accumulated. Once the required number of iterations is completed, the accumulated gradients are used to perform backpropagation. In the project's training loop, the backpropagation is done every 8 iterations.

Gradient Checkpointing

Given 32 decode layers, each implementing multi-headed attention, the methods mentioned above were not enough to reduce the memory consumption during training in order to fit into a single GPU. So, gradient checkpoint is implemented to reduce memory consumption during training further. In gradient checkpointing, activations required for backpropagations can be saved only for a selected few layers of the model. The activations of remaining layers will be forgotten as soon as they are used, and will be recalculated during the weight upgrade step respective layers during backward pass. Since the forward pass is recalculated for layers that forget their activations, the layers to the checkpoint should be carefully chosen in order to maintain a good balance between compute complexity and memory consumption. Checkpointing all the layers in the model will result in increased training time as all layers perform forward pass twice. So, we added checkpoints layer by layer by observing the memory consumption. The checkpoint library of PyTorch is used to add checkpoints to layers in the model. Going over the resources given in the project manual, firstly, we decided to checkpoint the layer in the model for every odd number of layers in 32 layers. Then, we checkpointed every layer that is not divisible by 4. This further reduced the memory consumption to approximately 32 GB. So now the model was fitting in one V100 GPU. In order to reduce memory consumption further, the checkpoints were gradually added to the feed-forward network. In order to support checkpointing for the feed-forward network, LoRA linear layers were used, with rank 2. We observed that as we checkpointed more and more layers, there was a slight increase in the

training time. Following is the summary of memory consumption and training time for various checkpoints -

Without checkpointing - caused the following error -
“

> **torch.cuda.OutOfMemoryError: CUDA out of memory.** Tried to allocate 250.00 MiB. GPU 0 has a total capacty of 39.59 GiB of which 202.12 MiB is free. Including non-PyTorch memory, this process has 39.39 GiB memory in use. Of the allocated memory 38.04 GiB is allocated by PyTorch, and 7.21 MiB is reserved by PyTorch but unallocated. If reserved but unallocated memory is large try setting max_split_size_mb to avoid fragmentation. See documentation for Memory Management and PYTORCH_CUDA_ALLOC_CONF

”

Layers checkpointed	**Memory Consumption**	**Time for 200 samples**	**Time for 300 samples**
Every odd layer	36741MiB	5 min	6 min
Every layer not divisible by 4	32421MiB	5 min	6 min
Every layer not divisible by 4 + query and key	31931MiB	7 min	10 min
Checkpointing every 4 + query and key + ffn gate and up proj	30617MiB	8 min	11 min
Checkpointing every 4 + query and key + all ffn projections	29729MiB	9 min	11 min

Result

Training Loss

epoch 4 sample - 0 loss - 0.15022309124469757
epoch 4 sample - 1 loss - 0.15893849730491638
epoch 4 sample - 2 loss - 0.07347355782985687
epoch 4 sample - 3 loss - 0.20515987277030945
epoch 4 sample - 4 loss - 0.11413722485303879
epoch 4 sample - 5 loss - 0.14735299348831177
epoch 4 sample - 6 loss - 0.18239068984985352
epoch 4 sample - 7 loss - 0.08757318556308746
epoch 4 sample - 8 loss - 0.10748983919620514
epoch 4 sample - 9 loss - 0.10378549247980118
epoch 4 sample - 10 loss - 0.05855221673846245
epoch 4 sample - 11 loss - 0.04993482679128647
epoch 4 sample - 12 loss - 0.12985244393348694
epoch 4 sample - 13 loss - 0.09758330881595612
epoch 4 sample - 14 loss - 0.05131136253476143
epoch 4 sample - 15 loss - 0.10237441211938858
epoch 4 sample - 16 loss - 0.06244099885225296
epoch 4 sample - 17 loss - 0.15503288805484772
epoch 4 sample - 18 loss - 0.2081546038389206
epoch 4 sample - 19 loss - 0.18586105108261108
epoch 4 sample - 20 loss - 0.06468472629785538
epoch 4 sample - 21 loss - 0.08913569897413254
epoch 4 sample - 22 loss - 0.03137857839465141
epoch 4 sample - 23 loss - 0.18736979365348816
epoch 4 sample - 24 loss - 0.14676374197006226
epoch 4 sample - 25 loss - 0.1700333058834076
epoch 4 sample - 26 loss - 0.04557425156235695
epoch 4 sample - 27 loss - 0.29165083169937134
epoch 4 sample - 28 loss - 0.09592558443546295
epoch 4 sample - 29 loss - 0.08043381571769714
epoch 4 sample - 30 loss - 0.059367552399635315
epoch 4 sample - 31 loss - 0.08671160787343979
epoch 4 sample - 32 loss - 0.0602993443608284
epoch 4 sample - 33 loss - 0.13480693101882935
epoch 4 sample - 34 loss - 0.1345340460538864
epoch 4 sample - 35 loss - 0.11111671477556229
epoch 4 sample - 36 loss - 0.14472171664237976
epoch 4 sample - 37 loss - 0.10591984540224075
epoch 4 sample - 38 loss - 0.18068070709705353
epoch 4 sample - 39 loss - 0.1410987675189972

epoch 4 sample - 40 loss - 0.1971873790025711
epoch 4 sample - 41 loss - 0.058846164494752884
epoch 4 sample - 42 loss - 0.19406668841838837
epoch 4 sample - 43 loss - 0.12564362585544586
epoch 4 sample - 44 loss - 0.16163665056228638
epoch 4 sample - 45 loss - 0.14526934921741486
epoch 4 sample - 46 loss - 0.1328786015510559
epoch 4 sample - 47 loss - 0.16798341274261475
epoch 4 sample - 48 loss - 0.040112219750881195
epoch 4 sample - 49 loss - 0.19421608746051788
epoch 4 sample - 50 loss - 0.17019030451774597
epoch 4 sample - 51 loss - 0.10967761278152466
epoch 4 sample - 52 loss - 0.1063530445098877
epoch 4 sample - 53 loss - 0.1650763750076294
epoch 4 sample - 54 loss - 0.15593072772026062
epoch 4 sample - 55 loss - 0.18153858184814453
epoch 4 sample - 56 loss - 0.18495845794677734
epoch 4 sample - 57 loss - 0.31240925192832947
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epoch 4 sample - 59 loss - 0.029696449637413025
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epoch 4 sample - 62 loss - 0.23374715447425842
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epoch 4 sample - 65 loss - 0.17656037211418152
epoch 4 sample - 66 loss - 0.06461925059556961
epoch 4 sample - 67 loss - 0.16319754719734192
epoch 4 sample - 68 loss - 0.10864555835723877
epoch 4 sample - 69 loss - 0.1609613299369812
epoch 4 sample - 70 loss - 0.168359637260437
epoch 4 sample - 71 loss - 0.24497090280056
epoch 4 sample - 72 loss - 0.18294672667980194
epoch 4 sample - 73 loss - 0.087644062936306
epoch 4 sample - 74 loss - 0.057323358952999115
epoch 4 sample - 75 loss - 0.10661794245243073
epoch 4 sample - 76 loss - 0.391147643327713
epoch 4 sample - 77 loss - 0.412321001291275
epoch 4 sample - 78 loss - 0.16710498929023743
epoch 4 sample - 79 loss - 0.13602298498153687
epoch 4 sample - 80 loss - 0.07665818184614182
epoch 4 sample - 81 loss - 0.07870914787054062
epoch 4 sample - 82 loss - 0.26972174644470215
epoch 4 sample - 83 loss - 0.16652829945087433

epoch 4 sample - 84 loss - 0.021437741816043854
epoch 4 sample - 85 loss - 0.1687021106481552
epoch 4 sample - 86 loss - 0.215477854013443
epoch 4 sample - 87 loss - 0.1606767475605011
epoch 4 sample - 88 loss - 0.16024285554885864
epoch 4 sample - 89 loss - 0.09705105423927307
epoch 4 sample - 90 loss - 0.14975406229496002
epoch 4 sample - 91 loss - 0.15419301390647888
epoch 4 sample - 92 loss - 0.12608149647712708
epoch 4 sample - 93 loss - 0.10141773521900177
epoch 4 sample - 94 loss - 0.13079553842544556
epoch 4 sample - 95 loss - 0.08995291590690613
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epoch 4 sample - 121 loss - 0.15191799402236938
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epoch 4 sample - 124 loss - 0.1936572939157486
epoch 4 sample - 125 loss - 0.20344719290733337
epoch 4 sample - 126 loss - 0.048794008791446686
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epoch 4 sample - 132 loss - 0.15428948402404785
epoch 4 sample - 133 loss - 0.071999192237854
epoch 4 sample - 134 loss - 0.09333992004394531
epoch 4 sample - 135 loss - 0.17418567836284637
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epoch 4 sample - 172 loss - 0.17813758552074432
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epoch 4 sample - 177 loss - 0.012093380093574524
epoch 4 sample - 178 loss - 0.020214514806866646
epoch 4 sample - 179 loss - 0.15585985779762268
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epoch 4 sample - 190 loss - 0.03500839322805405
epoch 4 sample - 191 loss - 0.1875215321779251
epoch 4 sample - 192 loss - 0.13451214134693146
epoch 4 sample - 193 loss - 0.18545381724834442
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epoch 4 sample - 196 loss - 0.08835504949092865
epoch 4 sample - 197 loss - 0.04780073091387749
epoch 4 sample - 198 loss - 0.12252433598041534
epoch 4 sample - 199 loss - 0.03280916064977646

With these incorporated techniques in the training loop, we successfully reduced memory consumption to 29,729 MiB, allowing the model to fit seamlessly on a single V100 GPU. The results for prompt-based inference were satisfactory.

Since the losses of each iteration during training can be viewed in the following link -

Inferences without fine tuning -

For prompts that are used for training -

Below is an instruction that describes a task, paired with an input that provides further context.

Write a response that appropriately completes the request.

"

Instruction:
For a given array arr, write a program to sort the array in-place without using any sort function.

Input:
arr = [5,7,3,9,10,1]

Response:
The response according to dataset - /n def sort(arr):
    n = len(arr)
    for i in range(n):

        min_idx = i
        for j in range(i+1, n):
            if arr[min_idx] > arr[j]:
                min_idx = j

        arr[i], arr[min_idx] = arr[min_idx], arr[i]

arr = [5, 7, 3, 9, 10, 1]
sort(arr)

print ("Sorted array:")
for i in range(len(arr)):
    print("%d" %arr[i]),
>Result generated by model before finetuning - /n
[5, 7, 3, 9, 10, 1]

Explanation:
Example 1:
Input:
arr = [5,7,3,9,10,1]

Output:
[5,

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Below is an instruction that describes a task, paired with an input that provides further context.
Write a response that appropriately completes the request.

"

Instruction:
Identify the historical events associated with the given location.

Input:
Rome

Response:
The response according to dataset - /n Rome is associated with many historical events, such as the founding of the Roman Empire, the rise and fall of the Roman Republic, the establishment of the Catholic Church and the rise of Christianity, the Building of the Colosseum and the Pantheon, and the fall of the Western Roman Empire.
>Result generated by model before finetuning - /n

The Colosseum is the most famous building in Rome. It was built in 72 AD and is still standing today. The Colosseum is one of the most well-preserved buildings from ancient Rome.

Examples:
```
Rome
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Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Classification. Is a zebra a mammal?

Response:
The response according to dataset - /n Yes, a zebra is a mammal.
>Result generated by model before finetuning - /n
Yes, it is.

Explanation:
A zebra is a mammal.

Challenge:
Is a zebra a reptile?

Explanation:

No, it is not.

Challenge:

==========

For prompts that are used for test-

Below is an instruction that describes a task, paired with an input that provides further context.
Write a response that appropriately completes the request.

"
Instruction:
Using the given text, create a five-sentence summary.

Input:
Rob was a ten-year-old boy who loved to play video games. Despite not having access to the latest console, he was well-versed in gaming culture and could create his own levels. He used this knowledge to design and build an impressive custom-made arcade cabinet for the village's annual carnival. His invention was an instant hit and Rob won the prize for best innovation.

Response:
The response according to dataset - /n Rob was a ten-year-old boy with a passion for video games. He had a strong knowledge of gaming culture and used this to create a custom-made arcade cabinet. His invention was a hit at the village's annual carnival, where Rob won the prize for best innovation. He used his gaming expertise to design and build the impressive cabinet without access to the latest console. His cabinet was a remarkable success.
>Result generated by model before finetuning - /n
"
Instruction:

Input:
Rob was a ten-year-old boy who loved to play video games. Despite not having access to the latest console, he was well-versed in gaming culture and could create his own levels. He used this knowledge to design and

==========

Below is an instruction that describes a task, paired with an input that provides further context.
Write a response that appropriately completes the request.

"
Instruction:

Calculate the angle of two vectors.

Input:
Vector A = (3, 4)
Vector B = (4, 3)

Response:
The response according to dataset - /n 45 degrees
>Result generated by model before finetuning - /n
The angle between two vectors is given by:

Explanation:
The dot product of two vectors is given by:

Notes:

Hints:

Solutions:

Examples:

Insights:

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Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Explain what the idiom "cut to the chase" means.

Response:
The response according to dataset - /n The idiom "cut to the chase" is used to mean to get to the point quickly and directly, without wasting time on irrelevant details. It originates as a film direction, indicating a scene should be edited out and the movie should move on to the important part of the plot.
>Result generated by model before finetuning - /n
Cut to the chase means to get to the point of the matter. It means to stop wasting time and get right to the point.

Instruction:

Explain what the idiom "cut to the chase" means.

Response:
Cut to

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Inferences of model produced on Trained prompts after finetune-

Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Predict what would be the kind of food that someone living in a tropical area would be likely to eat.

Response:
The response according to dataset - /n People living in tropical areas are likely to eat a variety of fruits, vegetables, fish, and other seafood. They will also enjoy various traditional dishes like rice and beans, plantains, starchy root vegetables and other local dishes such as soups, curries and stews.
>Result generated by model before finetuning - /n A person living in a tropical area would likely eat a diet that is high in fruits, vegetables, and fish. Tropical areas have a wide variety of fruits and vegetables available, and fish is a common source of protein. Additionally, tropical areas have access to a variety of spices and her

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Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Compose a 5-line poem about heartbreak.

Response:
The response according to dataset - /n Heartbreak so deep, it stains the soul
Pain so heavy, it won't let go
Nothing can fill the emptiness
Lost in a darkness so bottomless
Heartache that wilts the very rose.

>Result generated by model before finetuning - /n Heartbreak is a painful experience that can leave us feeling lost, confused, and alone. It is a feeling of intense sadness and longing, as if our heart has been shattered into a million pieces. It can be caused by the end of a relationship, the death of a loved one

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Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Generate an appropriate response to this instruction: "Describe the types of facial recognition technology used in security systems."

Response:
The response according to dataset - /n Facial recognition technology used in security systems can come in many forms, such as biometrics-based authentication, 3-D face recognition, or the use of algorithms to detect facial features. Biometrics-based authentication requires users to provide physical attributes such as fingerprints, iris scans, and facial recognition for access. 3-D face recognition is more secure and uses more than two-dimensional image recognition to identify a person. Algorithms can detect the shape, size, and position of facial features, allowing for more accurate verification.
>Result generated by model before finetuning - /n Facial recognition technology is a type of biometric security system that uses artificial intelligence algorithms to identify individuals based on their facial features. It is used in a variety of security applications, including airports, border crossings, and financial institutions. Facial recognition technology is typically more accurate than other forms of biometric security

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Inferences of model trained on 200 samples from test samples-

Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Name a language spoken in Africa.

Response:

The response according to dataset -
Arabic

>Result generated by trained model -
Swahili is a language spoken in Africa, and it is the most widely spoken language in the continent. It is spoken by over 100 million people and is the official language of Tanzania, Kenya, and Uganda. Swahili is a Bantu language and is closely related

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Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Create a speech to inspire people to help the environment.

Response:
The response according to dataset -
Good evening everyone. We are all here tonight to recognize the importance of taking care of the environment. We are all so fortunate to live on this beautiful planet and yet, many of us fail to recognize and preserve its beauty. Too often, we take for granted the clean air we breathe, the clean water we drink, and the abundant wildlife that populate our landscapes. It is our moral responsibility to take care of this planet and to ensure that our future generations can enjoy it just as much as we do. Our actions today will determine the future of our planet, so let us all work together to make it a better place for everyone. Let us be more conscious of our choices and preserve our planet for the greater good.

>Result generated by trained model -
Hello, everyone! I know we all want to make a positive impact on the environment, but sometimes we don't know where to start. That's why I'm here today to inspire you to take action and help the environment.Here are a few simple ways you can make a difference:Redu

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Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:

Describe the challenges and opportunities of mobile phone use in developing countries

Response:
The response according to dataset -
The use of mobile phones in developing countries can present challenges as well as many opportunities. On the one hand, access to mobile phones can reduce digital divides and enable access to information, education, and healthcare. However, there is also a lack of regulation, leading to a number of privacy and safety risks. Additionally, the technology can be difficult to use for users who lack education in technology and don't have access to reliable electricity. Nevertheless, when the technology is properly leveraged, the potential for good is enormous. For example, mobile phones have been used to improve healthcare outcomes and connect citizens with their governments.

>Result generated by trained model -
Mobile phone use in developing countries is a double-edged sword. On the one hand, it can provide a much-needed communication channel for people in remote areas who may not have access to traditional communication services. On the other hand, it can also lead to increased exposure to harmful content, such as

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Below is an instruction that describes a task, paired with an input that provides further context.
Write a response that appropriately completes the request.

"
Instruction:
Classify the given animal as a mammal.

Input:
Hedgehog

Response:
The response according to dataset -
yes

>Result generated by trained model -
The hedgehog is a mammal.

==========

Below is an instruction that describes a task, paired with an input that provides further context.
Write a response that appropriately completes the request.

"
Instruction:
Classify the following story as a fairy tale, urban legend, or horror story.

Input:
A young couple stumbled upon a haunted house in the woods.

Response:
The response according to dataset -
This is a horror story.

>Result generated by trained model -
This story is classified as a horror story.

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Inferences of model trained on 300 samples -

Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Tell me about the Great Wall of China

Response:
The response according to dataset -
The Great Wall of China is a series of fortifications made of stone, brick, tamped earth, wood, and other materials, generally built along an east-to-west line across the historical northern borders of China to protect the rate from invasions of various nomadic groups. It is the longest wall in the world, stretching 6,259 km (3,889 mi) from Shanhai Pass, near China's eastern coast, to Lop Nur in the westernmost part of China's Xinjiang region. It is over 2,000 years old and is considered one of the greatest engineering achievements of the ancient world.

>Result generated by trained model -

The Great Wall of China is one of the most iconic landmarks in the world. It is a series of fortifications built along the northern border of China from the 5th century BC to the 17th century AD. It is the longest man-made structure in the world, stretching over

==========

Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Write a command in SQL to delete all the data in a table called “Students”

Response:
The response according to dataset -
DELETE FROM Students;

>Result generated by trained model -
DELETE FROM Students;

==========

Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Create a headline for a blog post about the benefits of open source software.

Response:
The response according to dataset -
"Discover the Endless Benefits of Open Source Software!"

>Result generated by trained model -
Open source software is revolutionizing the tech industry, offering benefits such as increased security, flexibility, and accessibility.

==========

Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Identify the best strategies for running a successful business.

Response:
The response according to dataset -
Successful businesses require a number of strategies in order to thrive. Setting clear goals, creating and tracking performance metrics, establishing clear roles and responsibilities, utilizing data and analytics, and creating a feedback loop are important strategies for running a successful business. Additionally, having a positive company culture, treating employees well, and providing excellent customer service can help ensure business success.

>Result generated by trained model -
Effective communication, strategic planning, and a strong work ethic are key strategies for running a successful business. Communication is essential for building relationships with customers, employees, and other stakeholders. Strategic planning is important for setting goals and prioritizing tasks. A strong work ethic is

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Below is an instruction that describes a task.
Write a response that appropriately completes the request.

"
Instruction:
Name ten authors who have written works of science fiction / fantasy.

Response:
The response according to dataset -
J.R.R Tolkien, Neil Gaiman, C.S. Lewis, Ursula K. Le Guin, Isaac Asimov, George R.R. Martin, Stanislaw Lem, Frank Herbert, China Miéville, and Ray Bradbury.

>Result generated by trained model -
J.R.R.R. Tolkien, George R. R. Martin, J.K. Rowling, Neil Gaiman, Philip Pullman, Margaret Atwood, Ursula K. Le Guin, Octavia E. Butler, China Miéville, and N.K. J

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