Module 8: Portfolio Project Option 1 Part 1

Jocelyn Strmec

Colorado State University Global

CSC580 Applying Machine Learning and Neural Networks - Capstone

Pubali Banerjee

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Generative Adversarial Network (GAN) is a framework composed of an generative neural network and a discriminator neural network that parallelly oppose one another in order to strengthen the objective of both networks. The generative network objective is to generate realistic and believable content that will pass through detection and not be flagged as generated content. The discriminator neural network objective is to correctly differentiate and mark generated content versus real content. As the networks run against each other the quality of the generated content and ability to differentiate also increases in accuracy. The generated content is diverse because the generator can be a convolutional neural network (CNN), recurrent neural network (RNN), Transformers or any network depending on the intent of target generation content, the same goes for the discriminator. As such the GAN can be generating and discriminating images, music, audio, text or other such digital media. With such flexibility the applicability of GAN models is quite unbounded, across industries GANs can be utilized for search retrieval enhancement, historical preservation, ecological mapping, forensic and criminal investigative work. This paper will delve into these diverse applications of GANs across diverse industries and how adversarial training provides unique benefits in each domain.

Search is a seemingly simplistic problem: have data, search, find matching documents, and rank in order of relevance. However, this simplicity quickly falls apart when the queries people search are mistypen, synonyms, acronyms, discontinued items, vague ideas from large bodies of text, variants of measurements, other languages than anticipated, so on and so forth. As if that wasn’t enough complexity, it becomes even more difficult when the data being searched is irregular, inconsistent, incorrectly categorized, multiple content types such as PDFs, images, graphs, tables, text, video or audio. Most legacy search systems are text based using TF-IDF and BM25 with inverted indexes to search lexical matches with additional techniques that can be layered on other rules such as rule based boosting, burying pinning, and grouping for example. As of the last 10 years there has been an increasing switch into integrating semantic models with lexical to create a hybrid lexical and semantic search. Where GANs come in is in the content enrichment. An example is in ecommerce search where there will be a catalog of products a retailer wants users to be able to purchase. This retailer gets their products from many different sources, each of these sources has a way to name and tag their products with relevant details. When these products are amalgamated there are guaranteed to be discrepancies, however one commonality is that every product has a picture. To resolve this issue on the data ingestion side a GAN can be used to produce a few fields based on the image that focus on explaining the product, categories the product can be in, synonyms, and descriptions that are more unified in format and consistency. This makes a noticeable difference and increases searching efficiency and conversion for ecommerce sites. When addressing the query side challenges of search GAN can again be applied to increase the efficiency of results returned; however instead of capitalizing enrichment of the index from images, queries can be enriched via query expansion from the GAN. This technique of utilizing a GAN with a sequence-to-sequence encoder-decoder generator and an LSTM classifier for query expansion was first presented by Cakir & Gurkan (2023) as a way to increase token overlap between the pre-indexed content and the incoming query. This approach is similarly impactful in the recall of the search, meaning more relevant products can be surfaced. In both cases, index and query enrichment, the adversarial training mechanism produces high-quality enrichment based on image and text that increase relevancy and recall of search queries.

Beyond commercial search, GANs also serve as powerful tools in historical preservation. Well suited for enrichment, GAN's framework additionally excels at augmenting and recreating portions of images of ancient scripts, faded murals, or even helping visualize what an archaeological vase would have looked like. Historians, ancient language linguists, and archaeologists have the difficult position of trying to preserve and uncover artifacts and stories of periods long gone where incomplete and partial pieces of information or objects remain. This is very tedious and time consuming work that is often a race against time which further degrades the accessibility of the physical remnants. For digital archives with photographs, manuscripts, maps, and diaries GANs are perfect tools for correcting damage to the images, filling in smudges, torn pieces, or partial bits. The diversity of the generative network comes less into play as CNN types are more heavily used for this work. More so the quality of the generator is integral for accuracy of the augmentation so the historical artifacts are preserved to the fullest. When properly restored historians can focus on curation and categorization. For ancient Chinese scripts GANs are incredibly vital because keeping the font, character, and style is uniquely challenging to replicate except for a few experts and having enough time for these few individuals to make a dent in the vast sources of text needing to be restored and preserved is simply infeasible. A research group used this method to revive Yi and Qing dynasty texts and found a 6.7-8.0% accuracy increase in the structural integrity of the characters being maintained (Su et al., 2022). In terms of reducing the tedium of augmentation work, what would take historians 100s of hours is able to be done in only a few with the help of GANs, speeding up the rate history can be restored and accessible (Carneiro, 2024). Murals and artwork can be challenging to preserve because of size, placement, techniques, paints, and weathering or damage of each work. GAN networks composed of combinatory Transformer and CNNs are able to reconstruct mural features and match coloring, style, and work with as much accuracy as scientifically possible, preserving the art for further generations (Zhao et al., 2024). Contrary to the impression the previous examples might have made, GANs are also quite apt to apply to 3D renderings as they are 2D image representations. In cases of pottery reconstruction GANs can be incredibly impactful completing the scanned renders of broken vases and filling in the shapes to complete the render. This is a needed assistance because pottery is very rarely intact but due to age and time it is not possible to have all the broken pieces to reconstruct. Hermoza & Sipiran (2017) applied this technique on objects with half of the object missing for chairs, televisions, vases, and other common objects they could validate the accuracy of the reconstruction, proving how GANs can unburden artifact reconstruction. In the historical preservation efforts GANs are helping to restore images, volumes of scripts, maps, murals, artwork and artifacts with quality and precision that comes naturally from an adversarial trained generator.

Just as GANs help fill the gaps of our historical record, they are equally effective in addressing gaps in our understanding of the natural world. In ecological research, GANs contribute to monitoring, mapping, and forecasting critical environmental changes. As the terrestrial planet we live on is increasingly impacted by our species, knowing and mapping ecological zones, tracking, and awareness is pivotal to efforts to conserve, understand, guard the finite resources, and design better ways of living. Approximately three percent of the water on earth is fresh water and less than one percent is potable so there is a heavy importance of maintaining drinkable water's quality and continuing to clean and filter what is available. Monitoring water sources for pollutants is a necessary effort to ensure health and wellbeing of consumers, GANs can assist in this endeavor using a time series multivariate input that more accurately indicates a water contamination than monitoring singular chemical levels (Li et al., 2022). Other solutions such as support vector machines, ensemble stacking models and long short term memory models while able to utilize the time series data for predictions, are not able to account for the distribution of the metrics across the time period, resulting in more false alarms that reduce productivity and believability of alarms. Using a CNN time series data is able to be processed in a manner that allows the time flow to be more coherently understood by the model so the output summation image can be passed to the discriminator for deciding the validity of the anomaly event. This approach of using GANs is effective at reducing the number of false alarms and flagging anomalies that indicate water pollution. In broader applications GANs are suitable for refining and clearing obfuscation on satellite imagery to improve the geospatial datasets used for research, monitoring and increasing accessibility. Geospatial data is a key indication of metrics used to track climate change, however the resolution of most dataset is coarse because it is computationally expensive to capture more fine grained details (Li & Cao, 2025). Additionally clouds can present a quite frustrating challenge of obscuring the features under them, making the data incomplete without an effort to overlay multiple pictures of the same area and piece together the viewable parts. This approach of augmentation is time consuming and expensive. The solution for both troubles is applying a GAN to the collected satellite images, cleaning up passing clouds and enhancing the features of the coarse images so more clear fine-grained resolution is observable. This is a highly effective technique for removing cloud cover and making cloud-free images that are more useful for satellite-based remote sensing (Anandakrishnan et al., 2025). Research from Jozdani et al (2021) applied GANs with a similar aim on satellite imagery to increase quality and visibility for the purpose of mapping caribou lichen topology and are able to gain 10-20% increases in accuracy of mapping. Monitoring lichen is an ecosystem health indicator because lichen is sensitive to changes in climate, air quality, and disturbance. Disturbances in the lichen growth areas can serve as an early warning system for broader ecological shifts in boreal and tundra ecosystems. As climate disasters increasingly vary and strengthen, being able to reliably model weather and map at risk areas is very important for safety and preparation. Belhajjam et al.(2024) use GANs to replicate localized precipitation, simulate at extreme levels, to find patterns and map the most at-risk areas for flooding and damage. With the creation of flood risk maps the response of those in flood zones can be evacuated most quickly and preventative measures to prevent damage can be taken. Water quality, reliable ecological mapping, flood mapping and satellite datasets are very key to understanding and maintaining the health and well being of the ecosystem we all live in.

While ecology emphasizes collective survival, another domain where GANs make a striking impact is human safety and justice. In forensic and criminal investigations, GANs are being deployed to enhance evidence, identify suspects, and support critical decision-making. In cybersecurity forensics, GANs serve a dual role of generating synthetic attacks, and detecting deepfakes and other AI-driven manipulations, making them both a risk and a defensive tool in digital investigations. In many criminal cases when a victim or bystander has witnessed a crime and saw the perpetrator an artist is brought in to do sketches of the criminal. Sketches can be helpful but also are sometimes harder to find matches. GANs are an ideal tool to translate sketches into photo real images that can be used for facial recognition or more true to life depiction than a sketch can offer (Yun et al., 2024). This aids in investigations and suspect canvassing. Another use in criminology for GANs is in the aging of individuals. This is most commonly necessary for missing children and persons who can change significantly during the period of their absence. Efforts to age digitally have been around for many years though often relying on artists to infer the aging progression. This is tedious and requires the artist to have a strong understanding of aging’s impact on face shape, eyes, cheek fat, at what rate of changes happens at each age and to redraw when more time passes. GANs can speed up the process and create accurate age-progression and rejuvenation, through inputting in age and a reference photo (Chandaliya & Nain, 2022). This effectively reduces the time and allows for new images to be generated at regular intervals if the duration of time a person is missing goes on. Likewise for missing persons, the GANs can be used to age suspects, when previous evidence from photographs or sketches are available the same techniques can be applied (Sharma et al., 2021). Not only can GANs assist in sketching-to-photorealism and aging but video and image enhancement. In situations where the crime or criminal was digitally captured but the lighting was dim or the quality low, GANs can improve resolution up to four times, making the video more visible for investigators (Andrei et al., 2021). It should be noted that there are ethical and evidentiary concerns with using GANs because of subtle but systematic artifacts or hallucinations that may change the content of restored images or video. It becomes a question of the efficacy and usefulness of the GAN tooling versus the risk of altering evidence. This becomes an additional concern in the courtroom, where questions of admissibility and evidentiary integrity become central. While GAN-enhanced images may provide investigative leads, courts may hesitate to admit them as evidence without rigorous validation, fearing the risk of altered or hallucinated details. However, rather than discarding the GANs tools it requires a heavier importance on transparency from investigators on what tools they used, coming up with additional evidence, as well as the GAN having provenance, explainability, and external detection and validation pipelines.

Generative Adversarial Networks demonstrate remarkable versatility, finding applications from e-commerce search optimization to historical artifact restoration, ecological monitoring, and forensic investigation. What unites these diverse domains is the GAN’s ability to generate, refine, and enhance digital content with a level of realism that traditional models cannot match.

More than a technical innovation, GANs represent a shift in how industries handle incomplete, noisy, or inconsistent data and transform limitations into usable insights. Yet, their growing role also raises questions of ethics, transparency, and trust, particularly in fields like criminal justice and historical preservation where accuracy is paramount. Taken together, the evidence suggests that GANs are not merely tools for efficiency but catalysts for expanding what is possible in preservation, discovery, and decision-making. Their continued development will shape both the opportunities and the challenges at the intersection of technology and society.

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