Core Technologies in Semantic Search Engines

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ABSTRACT

Semantic search engines have revolutionized the way we retrieve information from the web by focusing on user intent and contextual meaning, rather than relying solely on keyword matching. This is enabled by core technologies like NLP, Knowledge Graphs, AI, ML. NLP helps search engines make sense of human language, allowing them to understand how words and phrases relate to each other. This utilizes Knowledge Graphs to improve search results, as this builds the data into relations, supplying the search engine with the ability to return more precise and contextual results. AI and ML algorithms work within search engines to improve the quality of outputs, learning based on interactions and helping to continuously improve ranking models. Further factors such as ontologies and entity recognition are involved in contextual awareness, allowing for more accurate responses to complex queries as well. Vector search with encoders moves us away from naive keyword search to allow much more semantically related and deeper search that fulfills a deeper connection of the user to the data. Semantic search engines are becoming more sophisticated as the digital landscape evolves, enabling such innovations as voice search; conversational AI; and recommendation systems. This review article describes these key pillars, their interdependencies, and their implications for the future of information retrieval, conveying that semantic search is transforming the next-generation intelligent search systems.

Keywords: Search Engine, Semantic Web, Natural Language process, Knowledge graphs, Artificial Intelligence, Machine Learning.

INTRODUCTION

Search engines have come a long way, from simple keyword-based retrieval systems to complex models that understand user intent and contextual relevance. Previously search engines such as Google used to match keywords exactly that were the reason the search results used to be irrelevant. Meaning and context are interpreted by using advanced technologies which overcome above-mentioned limitations which semantic search engines do.

Semantic Web Components-frame work:

The Semantic Web is an extension of the World Wide Web which allows data sharing across different kinds of applications. It adds meaning and relationships to web content through metadata, ontologies and linked data. Tim Berners-Lee proposed the Semantic Web, which refers to the intelligent and better data retrieval on the Web, which would help in search engines return results that are more relevant to the searchers. Which enables smooth data integration among different platforms bolstering automation, artificial intelligence powered apps and knowledge management.

Components and Framework of Semantic Web:

Components of Semantic Web:

One approach to extend the current web is the Semantic Web, and its purpose is to enable machines to better understand and link information (Berners-Lee et al., 2001). Its core components include:

(It was also a convenient standard for data interchange, representing information via subject-predicate-object triples, that made data machine-readable.)

OWL (Web Ontology Language): Used for defining rich relationships between entities, allowing for better categorization of knowledge hierarchically and in a more reasoned manner.

SPARQL: A powerful query language for querying and updating RDF-based linked data across multiple sources.

Knowledge Graphs: These help structure and relate data, allowing for a better understanding of context and making it easier for search engines and AI systems to provide more relevant and accurate results.

Frame work of Semantic Web:

Another example of Semantic Web technology is built upon semantic Web, where the data of the Web is processed is meaning full for the machines. These technologies combined approximate the work of structuring data, giving it relationships between it, and allowing it to be queried intelligently. The key components of this paradigm are Resource Description Framework (RDF), Web Ontology Language (OWL), SPARQL, and Linked Data. It is the combination of these parts that without which the Semantic Web cannot operate.

a) RDF (Resource Description Framework):

RDF is a standard to represent data on the web. It organizes information as triples, consisting of:

Entity – describes the target (e.g. 'Apple Inc.').

Predicate — The attribute or relation (e.g. "is a subtype of").

What – The value or relevant entity (ex. Technology Company)

Illustrative example: An RDF statement:

Five Sentence From "Apple Inc. is structured as:

In this case: Subject: Apple Inc. → Predicate: is a → Object: Technology Company.

This capability also enables interoperability between other sources of data such as XML documents, web pages, etc., through the use of common semantic vocabulary.

b) Web Ontology Language (OWL):

OWL: Web Ontology Language OWL stands for Web Ontology Language, which is a semantic markup language that extends RDF by adding more expressive relationships between data elements. It also establishes hierarchies, classifications and constraints to assist with reasoning. OWL is primarily used within the context of knowledge representation for applications in AI.

Key features of OWL include:

Class Hierarchies – Defines relationships like subclass and superclass (e.g., "Smartphones" is a subclass of "Electronics").

Property Restrictions − Defines restrictions on relationships (e.g., A human has exactly one biological mother).

Logical Inference – Allows AI systems to infer new knowledge from existing data (e.g., If "Dog is a Mammal" and "Mammals are Animals," then "Dog is an Animal").

These results in more structured and meaningful data that helps search engines and AI based sophisticated systems take better context-driven decisions.
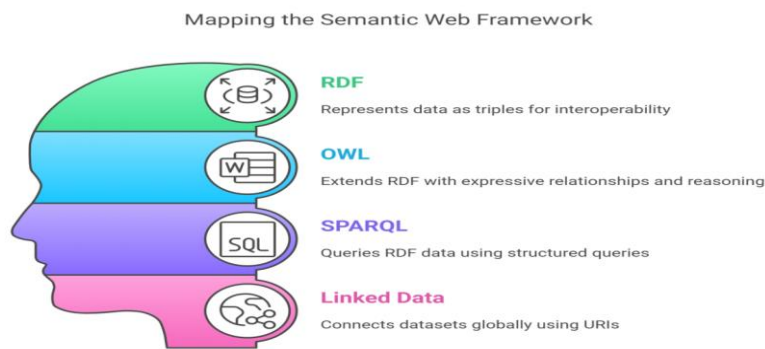

Figure.1 Frame Work of Semantic Web

c) SPARQL (SPARQL Protocol and RDF Query Language):

In fact, SPARQL is a query language uniquely designed for extracting and manipulating RDF data. SPARQL enables users to do the following, similar to SQL for a relational database:

Query RDF datasets using structured query.

Retrieve relevant data from massive and interconnected data sets.

Using advanced conditions to filter and manipulate data.

A SPARQL query, for instance to find all the books by a given author:

SPARQL

CopyEdit

SELECT? book WHERE {? book dc:creator "J.K. Rowling". }

All book titles where the author is J.K. Rowling are returned up.

Why Semantic Search? SPARQL lets users search for data based on relationships and meanings instead of keywords.

d) Linked Data:

It means an interconnectivity of datasets on the web, which creates a network of data that is linked all over the world. It is based on principles that include:

The use of Uniform Resource Identifiers (URIs) for each entity

Interlinking data and describing the relationship of entities through RDF.

Data collected in data sources is potentially very varied at both the syntax and semantics level as it is usually obtained in databases that can be very different from each other.

For instance, a knowledge graph can connect "Albert Einstein" with "Theory of Relativity", "Nobel Prize", and "Physics", enabling the search engine to grasp the context rather than simply treating these as isolated keywords.

It is the essential technology behind knowledge graphs, AI-enhanced search engines and recommendation engines that allows for data integration and interoperability across multiple domains.

Understanding the concept of Search Engines:

A search engine is basically an intricate program that is designed to search for the information stored on the internet or database on the basis of a user query and also displays the result accordingly. It does this by indexing billions of web pages and using algorithms to assess how relevant the results are. Search engines are essential in the digital age, allowing people to search for information simply by typing keywords or queries in natural language.

Types of Search Engines:

There are different types of search engines which are classified according to how they gather, index, and retrieve information. Some use automated bots, others rely on humans or powerful algorithms. This classification helps the users to know which search engine performs what functions and which one is best suitable for them. All types have their own merits and have made search smoother by adapting various retrieval methodologies and indexing systems to land more relevant and accurate results.
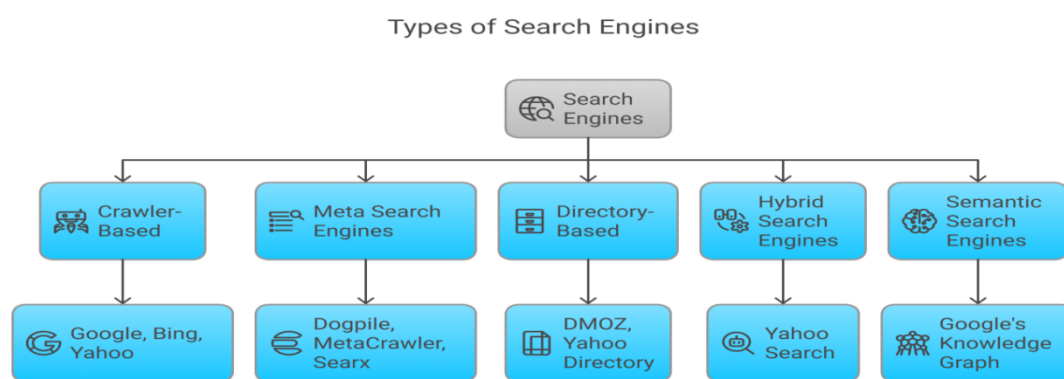

Figure.2 Types of Search Engines

Crawler-Based Search Engines

Crawler-based search engines rely on web crawlers (also referred to as spiders or bots) to automatically scan, index, and update web pages. These "crawlers" visit every link on a page, gather as much information as they can, before they go on to the next page, updating their databases. The search engine then retrieves results from this index based on ranking algorithms whenever users search for a query. Search engines like Google, Bing and Yahoo use advanced ranking mechanisms to provide relevant content based on keyword phrases, backlinks and page authority.

Meta Search Engines

So, there are actually no Meta search engines of their own databases, they take the results from various search engines and generate the single list. This allows users to gain a wider perspective on search results from various sources. Meta search engines remove duplicates and give users a range of responses. But often have limited ranking capabilities. Meta-search engines such as Dogpile, MetaCrawler, and Searx combine results from Google, Bing, and Yahoo for a more thorough query.

Search Engines Based on Directories

Directory-based search engines do not use automated crawlers; human editors categorize websites into topics and subtopics. These search engines are more structured and have excellent relevance because they manually

review the data, although this comes at the cost of a lack of scalability compared to automated systems. They were common before crawler-based search engines took over. The archival editors were hired to implement this assignment as DMOZ (Open Directory Project) and Yahoo Directory associate with various websites in directories.

Hybrid Search Engines

Hybrid search engines offer crawler-based indexing along with human-edited directory categorization for better search result accuracy. Those engines perform automatic indexing of new pages with web crawlers, but rely on editorial input with trusted source. Such a combination strikes a balance between automated efficiency and human judgement. Yahoo Search, for instance, started with a hybrid search engine model before shifting to Bing's crawled-based system to improve search performance.

Semantic Search Engines

Semantic search engine is based on the understanding of the concepts rather than just matching on keywords. These may use AI, Natural Language Processing (NLP), and Knowledge Graphs to understand query intent. These search engines provide more contextually relevant results, enhancing information retrieval accuracy. Examples of such systems include Google's Knowledge Graph, IBM Watson, and Wolfram Alpha, which leverage relationships between entities, concepts, and user behaviour in order to further refine search results.

Objectives of the Study:

The core objectives of the study are:

1. To analyze the core technologies behind semantic search engines.

2. To explore the role of contextual awareness in enhancing search accuracy

3. To examine the evolving capabilities of semantic search in next-generation intelligent systems

Earlier Study:

Thakker, D., Mishra, B. K., Abdullatif, A., Mazumdar, S., & Simpson, S. (2020). Highlight existing challenges with traditional AI in smart city solutions, such as the explainability issue in deep learning models. In response to the concerns of policymakers, it presents an Explainable AI approach for flood monitoring based on Semantic Web technologies. The proposed hybrid classifier achieves an 11% accuracy improvement over standard deep learning models by incorporating expert knowledge. The findings clearly show how integrating AI with domain knowledge can improve trust and make decisions in appropriate contexts for smart-city use cases. Chen X., Jia S., Xiang Y. Survey on knowledge graph reasoning: methods and applications. It emphasizes use-cases in knowledge completion, question answering Referenced: **Huang, M., & Rust, R. T. (2018)** presented a brilliant theory by examining how AI causes innovations and job replacement. It classifies service tasks into four intelligences—mechanical, analytical, intuitive, and empathetic—and explains why AI will progressively replace them at the task level. With the rise of AI, analytical abilities take a backseat while softer ones prevail. However, the integration of AI and humans also shows the clearer danger to job loss. This paper has very interesting insights into the implications of AI across the service industries. **J. Rashid, & M. W. Nisar (2016)** Described the benefits of Tsearch3 over a traditional keyword based engine. SSEs process vast amounts of data efficiently because they not only understand the intent behind the query but also return meaningful and defined results. The paper goes through their background, technology and existing comparative analysis of semantic search engines. **Socher, R., Bengio, Y., & Manning, C. D. (2012).** them highlights the effectiveness of Semantic Search Engines (SSE) compared to classical data search engines around keywords. By grasping what the users want, SSEs serve up clean relevant results while eliminating data overload. It includes semantic search background, technology, and comparative analysis of existing SSEs that have been developed and are increasingly important in managing and accessing a tremendous amount of information in the digital world. **Nagarajan, G., & Thyagharajan, K. (2012).** using

ontology to interpret syntactic web pages into semantic web pages to allow machine understanding and effective searchability. It helps you to provide semantics to the web and improves Semantic Web Learning technology, which helps to narrow the semantic gap between the way that humans and computers process information in the automation and information technology age. **Hitzler P, Krotzsch M, Rudolph S (2009).** Details a strong knowledge of Semantic Web standards, fruitful within RDF, OWL 2, RIF and SPARQL. It combines theory and praxis in ways that ground the reader in ontology engineering, formal semantics, and advanced querying strategies for the new digital ecosystems on the horizon. **Kassim, J. M., & Rahmany, M.(2009).** showcases the weaknesses of traditional search engines, including dependency on keywords and performance without the semantic understanding of context. This solves the problem by referring to semantic search engines in general, that improve the retrieval of information. The topic is relevant, but the writing could use shifting moods. Extending the analysis to semantic search techniques would also bolster the argument. The existing search engines focus on the location of information and do not consider semantics **(Li, Y., Wang, Y., & Huang, X., 2007)**. This paper presents OntoLook, a relation-oriented search engine for the Semantic Web. Figure ·The architecture and core algorithm of The study, and how it improves search accuracy. This type of research is progress towards more intelligent information retrieval on the internet. **Maedche, A., & Staab, S.(2001)** Discussed the importance of using ontologies for Semantic Web and illustrated a semiautomatic ontology learning framework. The authors improve traditional ontology engineering by incorporating ontology import, extraction, pruning, refinement, and evaluation. What I have learned from the study is that automation holds great potential for advancing the Semantic Web by improving the representation of structured data for machine understanding. **Jurafsky, D., & Martin, J. H.(2000).** Discussed in their book "Introduction to Speech and Language Processing Speech and Language Processing" that a comprehensive curriculum in natural language processing (NLP), computational linguistics, and speech recognition. Covering core subjects from conversational agents to machine translation and question answering, it examines linguistic structure, ambiguity resolution, and probabilistic models. It provides a foundation of theoretical concepts along with practical applications, making it useful for both students and researchers. The historical perspective gives it depth, and the notes about AI, Turing tests and machine learning make it clear that NLP is an ever-evolving field, which makes it essential reading for any language technologist.

Core Technologies in Semantic Search Engines

Natural Language Processing (NLP)

Natural Language Processing (NLP) is the branch of AI that enables search engines to comprehend the human language by analysing the text and drawing meaning from it. Major NLP techniques are tokenization (the way text is separated into words or phrases), stemming and lemmatization (reducing words to their root form), named entity recognition (NER for extracting names, places, dates), sentiment analysis (positive or negative) and syntax parsing (what grammatical structure is used). This makes the search more accurate as well as boosts the user experience significantly.

Tokenization: Breaking up text into individual words or phrases

Tokenization: the first step is to tokenize the text, that is, to break it down into smaller units (words, phrases, sentences). A Text Vectorization or Word Vectorization is one of the most important steps in any NLP because this is the way machines analyse and work on text. Two common types of tokenization include word tokenization, breaking the text into words, and sentence tokenization, breaking the text into sentences. Expansions include processing punctuation, contractions, and languages that do not have clear word delimiters (e.g. Chinese). By breaking text down into its constituent parts, tokenization provides structured input for subsequent NLP tasks, improving text parsing, sentiment analysis, and machine translation among other NLP applications.

POS (Part-of-Speech) Tagging: Understanding Grammatical Structure

POS tagging can assign grammatical categories (noun, verb, adjective) to words in a sentences in accordance to their uses and context. In fact, this process aids machines to comprehend the syntactical organization of a particular sentence, and thus is useful in various applications such as machine translation, text-to-speech

conversion, question-answering system, etc. POS tagging can be based on rules, statistical or deep learning methods to determine the role of the word. In the sentence "She runs fast," "runs" is a verb, and in "She enjoys morning runs," it's a noun. POS tagging provides accurate linguistic analysis and helps the downstream NLP tasks.

Entity Recognition (NER): Identifying People, Organization and Place Names

NER: Named Entity Recognition extracts and identifies certain entities, such as people, places, companies, dates, etc, within the text. It is a popular approach in search engines, chatbots, information retrieval, text summarization, etc. NER has two major steps: the first step is called entity detection, when we look for relevant words and the second step is called entity classification, when we put the relevant words into categories. In the sentence "Apple Inc. was founded in California by Steve Jobs," for example, NER identifies "Apple Inc." as an organization, "California" as a location, and "Steve Jobs" as a person. Advanced named entity recognition (NER) systems use a combination of deep learning and linguistic rules to yield better accuracy.

Social Media Interaction — Learning from Comments and Reviews

This process of analysing text for emotional tone — positive, negative, or neutral — is known as sentiment analysis, or opinion mining. This is a popular method for social media monitoring, product reviews, and customer feedback analysis. Lexicons and / or machine learning models and / or deep learning techniques for assessing emotions applied as sentiment analysis. For instance, "The movie was fantastic!" would fall under positive, while "The service was terrible, would be negative. Things like sarcasm, ambiguous context, and sentiment that mixed in the same sentence are the challenges. Sentiment analysis can help businesses, organizations make data-driven decisions based on public opinion.

Word Sense Disambiguation (WSD) is the process of determining which meaning of a word is used in context when it has multiple meanings. This is extremely important for NLP applications such as machine translate systems, search engines, question answering systems etc. In other words, in "I saw a bat in the cave," WSD helps determine whether "bat" means the flying mammal or a sports bat. Sensory data-based semantic disambiguation methods including: knowledge-based methods (such as dictionaries and ontologies), supervised learning (training models on labelled data), and unsupervised learning (clustering methods). WSD helps automate the processing of texts while identifying word meanings aids in understanding language for natural language tasks.

Knowledge Graphs: A knowledge graph structures information by linking entities and their relationships. Google's Knowledge Graph is a prime example, enhancing search results with interconnected data. Features include:

Entity Linking: Entity linking involves matching words or phrases from a search query to particular, relevant entities within a structured database, like a knowledge graph. It brings search engine two steps closer to knowing what the user is looking for by matching unclear terms to their correct definition. For instance, "Jaguar" could refer to a species name (i.e., an animal) or a brand (i.e., a car) and entity linking contextualizes the disambiguation.

Semantic Relationships: Semantic relationships help describe how different entities are related and improve search accuracy. These relationships are hierarchical (e.g., "Apple" is a type of "Fruit"), associative (e.g., "Doctor" and "Hospital"), and equivalent (e.g., "Car" and "Automobile"). Through this analysis, search engines gain insights about the deeper meanings of web pages and are able to offer users results that are more contextually relevant instead of solely keyword matches.

Contextual Awareness: By focusing on the broader network of information surrounding a query, contextual awareness contextualizes content and improves search results. Instead of treating words like isolated entities that require a manual match to find links that answer complex queries, it analyses related data, including past searches done by the user as well as their behaviour on the user's current search, to enhance answers.

Contextual Awareness: Search engines now understand context better how does a user search for "best universities" for example, get better ranked based on location, user preferences, rankings etc.

Artificial Intelligence (AI) and Machine Learning (ML) AI and ML play a crucial role in improving search accuracy by learning from user interactions and optimizing ranking algorithms. Key AI-driven techniques include:

Deep Learning Models: This includes using machine learning and natural language processing techniques which provide a high level of semantic context capture using deep learning models. Neural networks are examples of deep learning models that enhance query understanding by recognizing intricate patterns in text. Methods such as transformers (i.e. BERT, GPT) study context, synonyms and user intent to allow semantic search instead of basic keyword matching. These (or similar) models are being trained on huge amounts of text data so that they can enable search engines to provide better results by understanding the nuances of natural language and delivering better results based on what a user actually requested.

Reinforcement Learning: Reinforcement learning allows search engines to improve by receiving feedback through user interaction. Its evolution rewards and punishes relevant and irrelevant results, respectively, in a dynamic fashion that continuously refines ranking algorithms. The system can adapt to changing preferences by evaluating click-through rates, time spent reading articles, and user feedback, optimizing users' interests even better. By incorporating real user interaction data into search algorithms, this allows for continual improvement of search engines in response to how people actually conduct searches in the real world. A better metric is having a vector instead of a scalar for each word.

Vector Space Models: Vector space models (VSM) represent words as high-dimensional mathematical vectors in a vector space, where the relationship between the vectors represents semantic relationships based on the words' co-occurrence in context. Word2Vec, GloVe, and FastText are examples of techniques that enable search engines to comprehend word relations, similarities, and even analogies. VSM allows retrieval through semantic similarity, rather than exact keyword matches and retrieving results even with different words in the input query to get a result but with a matching concept. This improves the precision and relevance of search.

Ontologies and Semantic Web Ontologies are structures that lay out the use of vocabularies and relations in a domain. They aid search engines and AI in grasping context, relationships, and meanings, going beyond simple keywords. Ontology, through specialization of entities, attributes and relationships between the entities for semantic reasoning, helps in semantics representation of data for better information retrieval and interoperability.
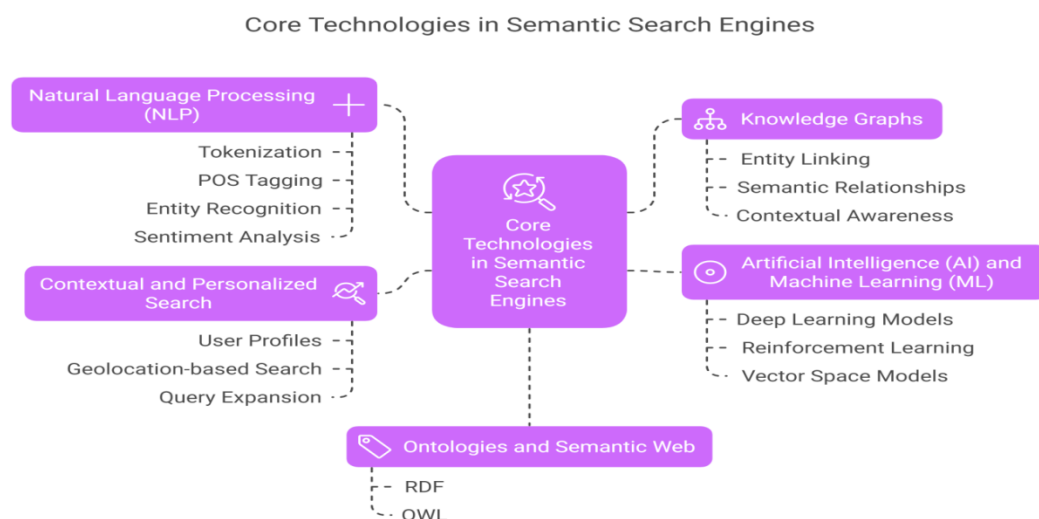

Figure.3 Core Technologies in Semantic Search Engines

Ontologies used in technologies such as RDF (Resource Description Framework) & OWL (Web Ontology Language) are the key component of the Semantic Web. RDF- serializes data to subject-predicate-object triples for machine readability, OWL- define complex relationships and hierarchies for better inference. SPARQL is a query language used to efficiently extract linked data.

The Semantic Web leads intelligent search, structured data integration, and better decision making by integrating these technologies. In the world of search, ontologies help search engines decipher user intent, link related concepts, and enhance the accuracy of search results, delivering more meaningful information retrieval across domains.

Contextual and Personalized Search Semantic search engines tailor results based on user history, preferences, and device context. Personalization techniques include:

User Profiles: o improves search relevance, user profiles are also used by search engines to evaluate past searches, past clicks, and user preferences. AI and machine learning algorithms recognize patterns, interests, and behaviour by monitoring search history to tailor search results. This way, users can get better predictions based on their context and needs. This means that if a user searches for the term "machine learning courses" multiple times, the search engine will prioritize displaying content related to machine learning, such as online courses, books, or research papers, on subsequent searches.

Geolocation-based Search Using geolocation in a search further enhances the accuracy of the search. The search engines thus provide localized results, such as nearby restaurants, stores, or events by using GPS, IP addresses, or Wi-Fi data. For instance, when someone searches for "libraries near me," the Google engine shows local libraries instead of entries here and there. Integrating location services - Essential for providing location relevant services such as local businesses, local search, and real-time updates (weather, transportation, and emergency notifications), keeping offerings relevant to end-users.

Query Expansion: Query expansion improves search results by predicting relevant words and proposing alternative queries. This technique allows consumers to locate pertinent information even when their query is limited in scope or infeasible to provide. These use synonyms expansion, stemming and semantic analysis to do so. For instance, when a user searches for "AI in healthcare," the system could recommend related topics, such as "machine learning in medicine" or "AI-driven diagnostics." The result is more effective search, helping users to find all-inclusive and substantive results.

Challenges and Future Directions

Despite their advancements, semantic search engines face challenges such as:

Ambiguity in Language: Natural language is vague; words can mean multiple things depending on how they are used. Search engines and AI find it really difficult with homonyms, metaphors, sarcasm and local vernacular. The word "bank" could be referring to a financial institution or a riverbank, for instance. NLP play an important role in disambiguation, techniques like WSD and contextual embeddings (like BERT, GPT) help resolving ambiguities based on sentence structure, surrounding words, and user intent. Better language comprehension enables more accurate search results and greater user satisfaction.

Scalability: The volume of information in the world is doubling every two years and managing structured (databases) and unstructured (text, pictures, and videos) data is a challenge with the growth of digital material. Search engines and AI models need to clear the indexing, search, and storage very quickly in real time. Scalability is increased through distributed computing, parallel processing, and cloud storage. Often, ranking algorithms based on machine learning help to highlight the relevant data while readjusting the computational burden. Scalability, when done well, serves to remove the friction of accessing information, enabling search engines to process billions of requests a day with a combination of accuracy and rapidity.

Privacy Concerns: Personalized search improves the experience, yet it poses issues with privacy as it implies data collection, storage, and utilization. Data security is essential even though AI-powered search engines with

end-user history, location, and preferences can narrow down search results. There are regulations like GDPR and CCPA that emphasize user consent and data encryption. Federated learning and differential privacy are privacy-preserving techniques that let AI models learn from user behaviour without revealing sensitive information. Maintaining the right level of personalization while respecting privacy helps build trust and promotes ethical AI usage.

Future researches: Improving AI, Multimodal and Real-Time Adaptability

The approaches have benefitted from advancements in AI which can help search by using multimodal search (technology that enables a better understanding of a query by combining text, images, voice, and video). Employing real-time adaptability in search engines, they can adjust results instantly based on the context of the query and the user's intent. The future will see more self-learning AI models with deeper functional contextual understanding, and enhanced conversational AI in user interaction. The integration of multimodal and adaptive search will further enhance the user experience of AI-powered search engines, making them more intuitive, accurate, and tailored to individual needs across a variety of domains.

CONCLUSION

Semantic search engines, utilization of AI, Natural Language Processing (NLP), knowledge graphs and ontologies, are revolutionizing how we seek information. Unlike traditional search engines, which operate primarily based on keywords, these engines utilize their comprehension of context, intent, and the interrelationship among concepts to deliver more meaningful and pertinent outcomes. Search engines are evolving—becoming more relevant and human-oriented—largely due to the advances in deep learning models, object recognition, and context sensitivity. Utilizing structured data and linking different information resources, semantic search increases the precision and relevant information retrieval in various fields, healthcare, education, business, e-Commerce, etc.

On the security front, semantic search engines will become even smarter, delivering more custom-tailored results based on user behaviour, preferences, and real-time data. But this will be exacerbated with the streaming of multimodal searches, which will integrate text, images, voice, and video. Moreover, as AI-based algorithms continuously improved over time, the real-time adaptability would also increase and fuel it to deal with complex queries in advanced search engines. Future advancements will also be guided by ethical considerations, like protecting individual privacy and mitigating bias. In the end, semantic search is transforming the way users discover and engage with information, providing more fluid, effective, and meaningful digital interactions in a world that is ever more driven by data.

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18. Figure1, Figure.2 and Figure.3 are generated by using napkin.ai by providing prompts.