DOE Commercial Building Benchmark Models

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ABSTRACT

The excitement surrounding the drive to build and renovate commercial buildings to achieve exemplary and even "net zero performance," coupled with the realization that complex systems engineering is usually required to achieve such levels, has led to a broader use of computer energy simulations. To provide a consistent baseline of comparison and save time conducting such simulations, the U.S. Department of Energy (DOE) – through three of its national laboratories – has developed a set of standard benchmark building models for new and existing buildings. These models represent a complete revision of the DOE benchmark buildings originally developed in 2006. The shapes, thermal zoning, and operation of the models are more indicative of real buildings than in the previous versions.

DOE has developed 15 benchmark buildings that represent most of the commercial building stock, across 16 locations (representing all U.S. climate zones) and with three vintages (new, pre-1980, and post-1980 construction). This paper will provide an executive summary overview of these benchmark buildings, and how they can save building analysts valuable time.

Fully documented and implemented to use with the EnergyPlus energy simulation program, the benchmark models are publicly available and new versions will be created to maintain compatibility with new releases of EnergyPlus. The benchmark buildings will form the basis for research on specific building technologies, energy code development, appliance standards, and measurement of progress toward DOE energy goals. Having a common starting point allows us to better share and compare research results and move forward to make more energy efficient buildings.

Introduction

The U.S. Department of Energy (DOE) conducts a large amount of research in commercial buildings at the national laboratories, private industry, and universities. The focus of the research is to develop the most energy efficient buildings and eventually reach zero energy buildings. This type of research relies heavily on whole building energy simulations, which are approached differently by each individual. To provide some standardization and to provide starting points for the researchers, DOE, working with the Lawrence Berkeley National Laboratory (LBNL), Pacific Northwest National Laboratory (PNNL), and the National Renewable Energy Laboratory (NREL) has developed standardized benchmark building models for energy simulations. The building models are developed for use with EnergyPlus Version 2.2 and will be updated for future versions (DOE 2008a). These benchmark building models represent approximately 70% of the commercial building energy use based on the 2003 Commercial Building Energy Consumption Survey (CBECS) (EIA 2005). There are three vintages of the building models meant to represent new construction, post-1980 construction, and pre-1980 construction. A companion paper presents a methodology for selecting envelope and HVAC systems from data on the existing building stock (Winiarski et al. 2008).

The primary users of the benchmark building models will be DOE sponsored research projects; however, the building models are likely to be used by other groups as starting points for their projects. Developing full models for detailed energy simulations is very time consuming and can be difficult to verify all the inputs. The DOE benchmark models have been carefully developed and reviewed by several researchers to increase confidence in their use. In addition, standardized models allow research results to be more easily compared. This paper describes the development of the benchmark building models and presents some results from running the models in EnergyPlus.

Background

Several previous projects focused on creating prototypical building models. Huang and his colleagues developed a series of prototypical buildings over several years (Huang et al. 1991; Huang and Franconi 1999) and another paper presents an analysis of 1999 building data (Huang et al. 2005). Two more recent efforts are a set of standardized energy simulation models for commercial buildings from the University of Massachusetts (Stocki et al. 2005) and a residential building benchmark from the DOE Building America program (NREL 2005).

The Building America benchmark was created to provide a common baseline for determining energy savings of proposed or existing residential buildings using hourly energy simulations. The size and location of the benchmark (baseline) building are set to match the proposed building, but everything else is defined by a set of modeling rules.

Huang et al. (1991) developed 481 prototypical commercial buildings (37 building types and 13 locations) for a market assessment of cogeneration systems. The building types, sizes, and locations were selected based on the best potential to use cogeneration. One objective of the project was to model the energy use in existing commercial building stock as closely as reasonable. The project paper presents an excellent summary of building characteristics databases, engineering studies, characterizations, and prototypes for energy simulations. The data used for the work included the Nonresidential Building Energy Consumption Survey, which later became CBECS, and F.W. Dodge building stock and forecast data. Huang and Franconi (1999) used 120 prototypical buildings covering 12 building types of old and new construction to estimate the heating and cooling loads in existing commercial buildings by component. The models were updated versions of the 1991 Huang et al. models based on 1989 CBECS data. Extrapolation of the models to represent the regional and national building stock was completed with weighting factors derived from the 1992 CBECS.

In an earlier version of this project, we developed simple models of the buildings (Deru et al. 2006). These building models were developed based on statistical averages of existing building stock for form (size and shape), but they had very simple geometry and uniform loads throughout the building. The current project provides building models that are much more complex and more representative of real buildings.

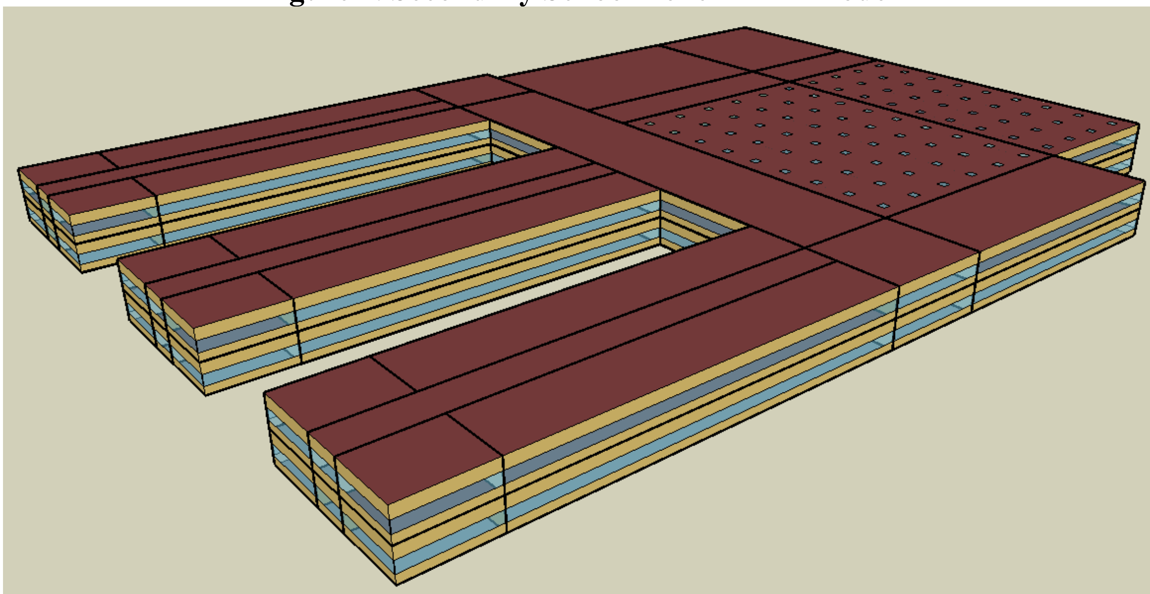
Approach

Representing most of the commercial building stock with a small set of building models is difficult because of the diversity of buildings and the limited data on existing buildings to draw from. We selected 15 building types based on analysis of the 1999 and 2003 CBECS, expert opinion of the existing building stock, and DOE research needs (EIA 2002, 2005). Table 1 lists the 15 building types along with some key parameters. LBNL developed the preliminary building model descriptions, focusing mainly on the form and thermal zoning based on typical building designs and previous research (Huang et al. 2005). NREL and PNNL then reviewed the models and filled in all the details of the building energy models. The models for the secondary school, primary school, and warehouse were taken from the ASHRAE Advanced Energy Design Guides (AEDG) projects conducted by NREL and PNNL. The benchmark building models were developed to be fairly realistic in appearance (Figure 1), in contrast to the DOE commercial building benchmark models created in 2006, which were simple single-zone or five-zone boxes.

Table 1. Benchmark Building Characteristics

Name	Floor Area ft^2	Number of Floors	Aspect Ratio	CBECS PBA	CBECS PBA+	2003 CBECS Area ft^2
Large Office	460,240	12	1.5	2	2, 3, 4, 5, 6, 7	228,725
Medium Office	53,630	3	1.5	2	2, 3, 4, 5, 6, 7	13,842
Small Office	5,500	1	1.5	2	2, 3, 4, 5, 6, 7	5,579
Warehouse	52,050	1	1.5	5	9, 10	21,603
Stand-Alone Retail	41,790	1	1.3	25	42	10,028
Strip Mall	24,010	1	3 (per store)	23, 24	50, 51	23,223
Primary School	73,960	2	E-shape	14	28	26,828
Secondary School	210,890	3	E-Shape	14	27, 29	37,024
Supermarket	45,000	1	1.3	6	14	8,314
Fast Food	2,500	1	1	15	32	3,345
Restaurant	5,500	1	1	15	33	6,585
Hospital	201,250	5	1.3	13	35	241,416
Outpatient Health Care	10,000	2	1.5	8	18,19	10,409
Small Hotel	21,080	2	L-shape	18	39	14,990
Large Hotel	100,820	6	3.8 (1st flr) 5.1	18	38	97,102

Figure 1. Secondary School Benchmark Model



Energy models of buildings contain many details that are not available from standard data sources. Several assumptions had to be made to complete the models. These assumptions include thermal zoning, aspect ratio, orientation, number of floors, window to wall ratios, HVAC types, internal loading, and schedules. We have divided the building description into four areas: program, form, fabric, and equipment Table **Error! Bookmark not defined.**.

Table 2. Input Parameter Categories

Program	Form	Fabric	Equipment
Location	Number of floors	Exterior walls	HVAC system types
Total floor area	Aspect ratio	Roof	Component efficiency
Schedules	Window fraction	Windows	Control settings
Plug and process loads	Window locations	Interior partitions	Lighting fixtures
Lighting densities	Shading	Internal mass	Lamp types
Ventilation needs	Floor height		Daylighting controls
Occupancy	Orientation		

PNNL developed white papers with recommendations for the locations, constructions, and HVAC types based on analysis of CBECS and expert opinion. NREL developed the balance of the input files, including the schedules and internal loading. NREL also took the lead on developing and maintaining the input files and documenting the models.

The building size and number of floors were selected to be representative of existing and new buildings, which is very difficult with a small number of benchmark models. The main source of data is the 2003 CBECS using the principal building activity (PBA) and the PBAPlus categorization of buildings. The size and shape of the 15 buildings are listed in Table 1 along with the average size for each building type from 2003 CBECS. The size, number of floors and shape are kept constant across all locations and across the three vintages of benchmark building models. We made this assumption because the data are lacking for better resolution with time and space and it allows for better comparisons of energy features across locations.

The benchmark project team selected 16 locations based on representativeness of the climate zones and population centers in the climate zones following a white paper from PNNL (see Table 3). These locations are not the same as those selected to be representative of the climate zones by PNNL in development of the ASHRAE climate zones (Briggs et al. 2003). In addition, we selected two cities for climate zone 3B. Most of climate zone 3B is characterized by hot and dry summers and cool winters similar to Las Vegas, but the benchmark team felt that Los Angeles represents a different climate, which is shown in the results of running the models.

Table 3. Selected Commercial Building Benchmark Locations

Number	Climate Zone	Representative City	TMY2 Weather file location
1	1A	Miami, FL	Miami, FL
2	2A	Houston, TX	Houston, TX
3	2B	Phoenix, AZ	Phoenix, AZ
4	3A	Atlanta, GA	Atlanta, GA
5	3B	Los Angeles, CA	Los Angeles, CA
6	3B	Las Vegas, NV	Las Vegas, NV
7	3C	San Francisco, CA	San Francisco, CA
8	4A	Baltimore, MD	Baltimore, MD
9	4B	Albuquerque, NM	Albuquerque, NM
10	4C	Seattle, WA	Seattle, WA
11	5A	Chicago, IL	Chicago-O'Hare, IL
12	5B	Denver, CO	Boulder, CO
13	6A	Minneapolis, MN	Minneapolis MN
14	6B	Helena, MT	Helena, MT
15	7	Duluth, MN	Duluth, MN
16	8	Fairbanks, AK	Fairbanks, AK

The remaining program parameters cover the operation of the building. We assumed that internal loads and operating schedules are the same for all locations and vintages of benchmark building models. For operating schedules, we started with those from ASHRAE Standard 90.1-1989 and the slightly revised versions in the ASHRAE Standard 90.1-2004 User's Manual (ASHRAE 1989, 2004b). The first modification we made was to add a separate plug load schedule and increase the plug load intensity during unoccupied periods based on data from building monitoring activities at NREL. Next, we developed separate schedules for zones with different operations. For example, the school models have extended hour schedules for some classrooms, the gymnasium, and the auditorium. Lighting loads, plug loads, and ventilation requirements vary by zone to provide fairly realistic operations. The lighting load densities for new construction follow the Standard 90.1-2004 requirements, and the pre- and post-1980 benchmark models use the values from Standard 90.1-1989 (ASHRAE 1989, 2004a). We assumed that most of the older buildings have been updated to the 90.1-1989 levels. The electricity and gas plug or process load densities by zone were based on a combination of previous research, current research, and best judgment. The complete listing of this information is contained in the full project report, which will be published as a DOE technical paper. Several of the models contain commercial kitchens, which have large process loads, refrigeration, and high make-up air requirements. Walk-in style coolers and freezers are included in all the kitchens based on data from an Arthur D. Little, Inc. study on commercial refrigeration systems (Westphalen et al. 1996). The kitchen electricity and gas process loads and the exhaust flow were based on review of ASHRAE Journal articles (Brown 2007 and Fisher 2003), data from the Commercial Kitchen Design Guides (CEC 2004 and SGE 2004), and a review of kitchen designs. Transfer air from adjacent zones is used for part of the make-up air requirements for the kitchens. The refrigeration systems in the super market benchmark model are based on prior reports (Faramarzi and Walker 2004) and current work with large grocery retailers.

The envelope parameters include the wall, roof, and floor constructions; window types; and the thermal parameters of these objects. The roof and wall construction types listed in Tables 4 and 5 were determined from an analysis of the 2003 CBECS data and other information by PNNL (Winiarski et al. 2008). One set of construction types was determined for the pre-1980 buildings and another for the post-1980 and new construction buildings. The wall, roof, and window thermal parameters for the new construction benchmark models are set to the Standard 90.1-2004 values, and Standard 90.1-1989 was used for the post-1980 benchmark models. The wall, roof, and window thermal parameters for the pre-1980 models were assumed to be the 1960 office building construction estimates from Briggs et al. (1987).

Table 4. Recommended Roof Constructions by Building Type

Building Type	Pre-1980	Post-1980	New Construction
Large Office	Ins. above deck	Ins. above deck	Ins. above deck
Medium Office	Ins. above deck	Ins. above deck	Ins. above deck
Small Office	Ins. above deck	Attic and other	Attic and other
Warehouse	Ins. above deck	Metal building roof	Metal building roof
Stand-Alone Retail	Ins. above deck	Ins. above deck	Ins. above deck
Strip Mall	Ins. above deck	Ins. above deck	Ins. above deck
Primary School	Ins. above deck	Ins. above deck	Ins. above deck
Secondary School	Ins. above deck	Ins. above deck	Ins. above deck
Supermarket	Ins. above deck	Ins. above deck	Ins. above deck
Fast Food	Ins. above deck	Attic and other	Attic and other
Restaurant	Ins. above deck	Attic and other	Attic and other
Hospital	Ins. above deck	Ins. above deck	Ins. above deck
Outpatient Health Care	Ins. above deck	Attic and other	Attic and other
Motel	Attic and other	Attic and other	Attic and other
Hotel	Ins. above deck	Ins. above deck	Ins. above deck

Table 5. Recommended Wall Constructions by Building Type

Building Type	Pre-1980	Post-1980	New Construction
Large Office	Mass wall	Mass wall	Mass wall
Medium Office	Steel frame wall	Steel frame wall	Steel frame wall
Small Office	Steel frame wall	Mass wall	Mass wall
Warehouse	Metal building wall	Metal building wall	Metal building wall
Stand-Alone Retail	Steel frame wall	Mass wall	Mass wall
Strip Mall	Steel frame wall	Steel frame wall	Steel frame wall
Primary School	Steel frame wall	Steel frame wall	Steel frame wall
Secondary School	Steel frame wall	Steel frame wall	Steel frame wall
Supermarket	Mass wall	Mass wall	Mass wall
Fast Food	Mass wall	Wood frame wall	Wood frame wall
Restaurant	Steel frame wall	Steel frame wall	Steel frame wall
Hospital	Mass wall	Mass wall	Mass wall
Outpatient Health Care	Steel frame wall	Steel frame wall	Steel frame wall
Motel	Steel frame wall	Steel frame wall	Steel frame wall
Hotel	Mass wall	Mass wall	Mass wall

The HVAC system types were determined by an analysis of the 2003 CBECS data and other sources by PNNL (Winiarski et al. 2008). Table 6 shows the HVAC equipment for the post-1980 and new construction benchmark models and Table **Error! Bookmark not defined.** shows the equipment for the pre-1980 benchmark models. The schools, hospitals, hotel, and motel have multiple system types to serve different zones. The equipment efficiencies are based on Standard 90.1-2004 for new construction, Standard 90.1-1989 for the post-1980 models, and an analysis of energy codes from PNNL for the pre-1980 models.

Table 6. HVAC Equipment for Post-1980 and New Construction

Building Type	Heating	Cooling	Air Distribution
Large Office	Boiler	Chiller	MZ VAV
Medium Office	Furnace	PACU	MZ VAV
Small Office	Furnace	PACU	SZ CAV
Warehouse	Furnace	PACU	SZ CAV
Stand-Alone Retail	Furnace	PACU	SZ CAV
Strip Mall	Furnace	PACU	SZ CAV
Primary School	Boiler	PACU	CAV *
Secondary School	Boiler	Chiller	MZ VAV
Supermarket	Furnace	PACU	CAV *
Fast Food	Furnace	PACU	SZ CAV
Restaurant	Furnace	PACU	SZ CAV
Hospital	Boiler	Chiller	FCU, CAV and VAV**
Outpatient Health Care	Furnace	PACU	CAV *
Motel	ISH	IRAC	SZ CAV
Hotel	Boiler	Chiller	FCU and VAV***

Table 7. HVAC Equipment for Pre-1980 Construction

Building Type	Heating	Cooling	Air Distribution
Large Office	Heating	Cooling	Air Distribution
Medium Office	Boiler	Chiller	MZ VAV
Small Office	Furnace	PACU	SZ CAV
Warehouse	Furnace	PACU	SZ CAV
Stand-Alone Retail	Furnace	PACU	SZ CAV
Strip Mall	Furnace	PACU	SZ CAV
Primary School	NA	NA	NA
Secondary School	Boiler	PACU	CAV *
Supermarket	Boiler	PACU	CAV *
Fast Food	Furnace	PACU	CAV *
Restaurant	Furnace	PACU	SZ CAV
Hospital	Furnace	PACU	SZ CAV
Outpatient Health Care	Boiler	Chiller	FCU, CAV and VAV**
Motel	Furnace	PACU	CAV *
Hotel	ISH	IRAC	SZ CAV

PACU – Packaged Air Conditioning Unit   ISH – Individual Space Heater
IRAC – Individual Room Air Conditioner
SZ - Single Zone   MZ - Multizone
CAV - Constant Volume   VAV – Variable Air Volume
FCU – Fan Coil Units
* Unclear if single zone or multizone

** Hospitals may use constant volume systems in some operating and critical care type areas with variable air flow used for pressurization, but classic VAV multizone systems in other areas such as offices. CBECS guidance seems limited here and other sources should be consulted. CBECS Buildings reporting VAVs are significantly less common before 1980 (67% versus 95% in post-1980 hospitals).

*** Hotels may be characterized with two system types serving different areas. Both multizone systems (VAV and CAV) may serve public spaces (lobby/conference rooms), whereas single zone fan coil systems may be common for living areas.

All the models will be publicly available after peer review with a project report, spreadsheet "scorecards," and EnergyPlus input files (DOE 2008b). The EnergyPlus input files are written by Opt-E-Plus, NREL's simulation and optimization platform that auto generates EnergyPlus input files based on an xml file that contains high level building model descriptions. There is one master xml file for each building type and vintage that is used to generate the other files. Therefore, we only need to maintain one file per building type. The location dependent information is contained in the Opt-E-Plus application, which creates the EnergyPlus input file for any location defined in the program and manages running all files with EnergyPlus over a distributed computer network or on a local multiprocessor machine.

Results

All the models were run with EnergyPlus version 2.2 (DOE 2008a). The site energy use intensities for the new construction benchmarks for the 16 locations are shown in Table 8, along with the average from 2003 CBECS for comparison purposes. We are not attempting to match the CBECS energy use numbers, and no conclusions beyond general trends in the data should be drawn by comparisons between the new construction benchmark models and CBECS.

Table 8. Benchmark Site Annual Energy Use Intensities for New Construction (1000Btu/ft^2)

City	Miami	Houston	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks	2003 CBECS Average
Climate Zone / Building	**1A**	**2A**	**2B**	**3A**	**3B**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**	**8**	
Large Office	49.5	51.5	51.1	49.2	42.6	53.3	42.6	52.6	51.4	44.8	51.5	52.7	54.7	56.7	55.9	68.0	98.6
Medium Office	48.3	49.0	50.6	47.5	41.3	47.2	42.0	50.9	46.5	44.7	50.1	47.6	53.9	50.6	54.8	66.3	93.8
Small Office	36.7	33.6	35.2	29.1	26.1	30.1	26.1	30.5	28.9	28.2	31.7	29.4	34.6	32.1	35.3	47.3	79.9
Warehouse	18.2	21.4	21.8	26.6	17.9	24.4	25.1	34.7	29.6	32.9	42.0	36.9	53.3	47.9	58.5	87.6	47.8
Stand-Alone Retail	37.4	33.7	33.8	32.0	30.1	33.1	29.8	32.6	32.1	30.3	32.8	32.0	34.8	33.3	35.1	41.1	70.1
Strip Mall	38.1	36.2	37.6	35.2	29.2	36.1	32.3	38.5	36.3	35.4	40.9	37.9	46.6	43.5	48.5	63.4	110.0
Primary School	94.5	93.0	91.3	85.5	72.3	82.5	91.8	92.9	82.5	79.5	100.0	88.0	115.2	99.9	121.8	165.5	68.3
Secondary School	86.5	85.0	92.3	78.8	66.4	83.0	84.7	85.1	81.7	71.0	88.9	84.2	100.6	92.5	105.2	144.0	79.9
Supermarket	180.9	185.4	171.7	180.8	158.4	163.6	167.3	191.0	171.8	181.1	200.1	181.3	213.6	197.0	222.1	264.1	214.4
Fast Food	454.5	464.4	431.7	476.2	365.9	439.5	400.3	552.5	483.1	486.1	621.6	543.5	709.1	626.1	781.3	1043.6	450.9
Restaurant	260.4	266.4	249.0	274.7	204.0	253.7	228.7	324.5	278.4	283.2	366.4	314.6	421.0	367.0	464.0	633.1	231.2
Hospital	126.1	128.7	132.5	121.9	99.8	122.6	107.8	132.6	123.9	113.6	140.6	130.3	154.2	140.2	161.3	206.8	249.2
Outpatient Health Care	40.2	37.0	37.7	34.4	29.7	35.6	29.1	36.8	34.4	32.5	37.5	34.1	41.5	37.3	41.2	56.0	94.6
Small Hotel	60.7	60.3	59.4	60.6	58.0	59.1	58.4	63.4	63.5	61.0	67.2	66.2	73.2	70.6	77.6	92.5	74.9
Large Hotel	68.3	72.9	75.9	64.7	50.3	63.8	57.6	73.7	65.3	65.5	81.1	70.3	90.8	80.3	95.8	129.2	110.0

Conclusions

We have been successful in developing commercial benchmark building models for 15 building types, 3 vintages of buildings, and 16 locations for energy analysis research. These models represent the work of numerous individuals over several years; however, they are not static. The models will be updated with new releases of EnergyPlus, and they will evolve as we gain more knowledge about building operations and new research requirements develop. The models are presented in EnergyPlus input files, but they could also be translated for other energy simulation programs.

The benchmark building models represent a starting point for analysis projects. They can be used with weighting factors to model the effect of energy efficiency technologies on all or part of the building stock, or they can be used without the weighting factors to understand the effects of energy efficient technologies on specific building types in different climates. The benchmark building models will be used as the basis for DOE research programs and to evaluate the effectiveness of DOE research programs. In addition, they will be used by ASHRAE for analysis and development of energy standards. It is also anticipated that they will be used by other building research activities, and they will modified by the users to fit the needs of their projects. The main benefit of the standardized benchmark models is that they form a common point of comparison between research projects.

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