Designing Patient-Oriented Healthcare Services as Systems of Systems

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***Abstract*—Chronic diseases are on the rise, increasing in number and complexity. Consequently, the needs of patients with chronic diseases are increasing and becoming more complex and multi-faceted; they require addressing not only the physical body, but also behavioral, emotional, spiritual health.**

The current healthcare delivery system organically developed to address acute conditions, primarily injury and infection during the mid-19th century, a time when the body was viewed as a machine. This led to the organization of the healthcare delivery system by organ systems into specialties and departments. However, the healthcare delivery system today needs to provide healthcare services that span multiple systems to provide the care patients need. Such care requires services from multiple specialties (e.g., podiatry and endocrinology for diabetes, primary care and psychiatry for behavioral health, and palliative care MDs and chaplains & social workers for end-of-life care) that each effectively functions as its own system.

There are currently several limitations and difficulties in designing patient-oriented healthcare services utilizing systems of systems. First, clinical models describe the service with a focus on resources. Second, the description tends to be at a high-level of abstraction, leaving the details to the implementer. Finally, the patient is generally modeled as an operand non-participatory agent, being pushed and pulled through the system.

This paper describes the use of engineering and systems principles to design patient-oriented healthcare services that provide *detail* and *quantification* that classic services do not model. In doing so, these designed system of system models incorporate the detail, data quantification and implementation level information to allow for the success of the clinical aspect of the model to be achieved. This paper presents a medical based description of a system of systems and the engineered system based description of an integrated patient oriented service.

I. Introduction

Chronic conditions on the rise, increasing in number and complexity. In the first time in history, our children's generation are expected to lead shorter life spans than our own [1]. Chronic conditions, unlike acute conditions, are particularly complex in that they tend to involve multiple factors with multiple interactions between them [2]. It is now established that combating chronic disease requires treating the patient more holistically [2]–[9]. This is currently a challenge given that the science of clinical medicine is fundamentally reductionist [2]. Clinical medicine needs to evolve and shift to specifically provide needed services that address the growing chronic disease epidemic.

The current healthcare delivery system organically developed to meet "one-off" acute conditions. In doing so, it evolved and expanded based on a reductionist view of the physical body, based on organs and organ systems (i.e. cardiology, endocrinology, podiatry, etc.). Current chronic conditions however, make up over 78% of total healthcare costs in the United States [10]. Many published work are recognizing the value, especially in terms of patient outcomes, when these services are restructured to focus on a patient-oriented experience and needs rather than the classically acute care based separation of specialty []. Therefore, more and more healthcare systems have recognized the need to provide single-point services classically provided by multiple different healthcare departments or systems (e.g., primary care and behavioral health, palliative care and cancer).

Now that healthcare recognizes the need to provide services tailored to patients with chronic diseases, it uses classical clinical constructs typical in medicine to design such services. The first is based on classic description of models in healthcare and the second is based on how the patient is perceived.

The first clinical construct is based on clinical models that describe services with a focus on resources from a high-level of abstraction. Given the resource focus in healthcare, designing services typically describes services from a human personnel resource perspective at the expense of describing the function of these human resources. This is a problem for three reasons.

First, by describing a human resource, clinical medicine alludes to the functions that personnel resource can provide. This is based on the classic Medical Degree (MD) education, training and certification processes which provides a clear description of scope of work for such a personnel. However, some of the fastest growing resources in healthcare are non-MD personnel [11]. While many of these non-MD clinicians (i.e., nurses, medical assistant, behavioral specialist, social worker) also have education programs and certifications, they do have a much wider of scope of work.

Second, creating services by bringing together personnel from different systems brings together individuals to a team where clinical language, culture and operations may differ significantly. By not specifically addressing scope of work or tasks of each personnel, leaves the large possibility for misunderstanding and leaves the behavioral dynamics of the team to be reduced to the individual personalities. Bringing together human resources from different systems requires the explicit description of not only individual scope of work, but also team scope of work.

Finally, while some integrated services may describe general tasks for allocated resources, system of system boundaries are not defined. At the system boundary is where many key functions needed to allow the team to function well are not defined and if defined, not allocated to resources at the appropriate value (i.e., value in terms of time to perform task or payment for tasks). For example, curbside consults of primary care physicians with integrated behavioral health specialists is key for helping identify the best decisions for patient care needs. It also serves as a teaching and educational moment, that is in many cases underutilized. Similarly in palliative care, the interactions of palliative care providers, specialists such as oncologists and other service providers such as chaplancey or social services amongst others, are key to helping identify the best decisions that most appropriately conform with patient's needs and wishes.

The second clinical construct models the patient as an non-participatory operand agent, being pushed and pulled through the system. There have been significant efforts to shift the discussion of clinical decision making from the clinician to a shared-decision between the patient and clinician. Research in shared-decision making [12] shows significant improvements in patient reported outcomes with such an approach. While clinical medicine is slowly adopting shared-decision making for critical conditions or severe-illness, the focus of shared-decision making is made at specific times rather than for every healthcare system interaction with the patient. By taking into account patient choice at each level of the modeling, the model is developed to allow for quantification of not only the services provided but to which patients and with what outcomes.

A. Paper Contribution

This paper presents an application of systems of systems engineering using a system model framework [13] and model-based systems engineering [14] to design a patient-oriented integrated healthcare service. A behavioral health integration into primary care is presented first with the original *clinical model* and then presented and described using the developed emphsystem model.

B. Paper Outline

The background in Section II presents a system model for personalized healthcare delivery as a systems of systems framework. Next, the methodology for designing an integrated behavioral health in primary care healthcare service as a system model is described in Section III. The resulting system model and original clinical model are described in Section IV. Finally, conclusions are presented in Section V.

II. Background

Designing Patient-Oriented Healthcare Services as Systems of Systems rests upon the developed architecture for personalized healthcare delivery and managed individual health outcomes [15]. That work drew upon a hetero-functional graph theory rooted in the Axiomatic Design for Large Flexible Engineering Systems and Petri nets. The healthcare delivery system form is described by its resources in Section II-A, and its system function is described by processes in Section II-B. The processes are allocated to resources in the system concept as described by the system knowledge base in Section II-C.

A. System Form

The healthcare delivery system is composed of resources representing system form. Four types of resources $\mathbb{R} = \mathbb{R}_F \cup \mathbb{R}_D \cup \mathbb{R}_M \cup \mathbb{R}_N$ have been defined [15] :

Definition 1. Transformation Resource: A resource $\mathbb{r}_F \in \mathbb{R}_F$ capable of a transformative effect on its operand (e.g. the health state of an individual). They include *human* transformation resources $r_F \in R_F$ (e.g. surgeon, cardiologist, psychologist) and *technical* transformation resources $\mathscr{r}_F \in \mathscr{R}_F$ (e.g. operating theaters, chemotherapy infusion room, delivery room). Transformation resources are the set union of human and technical transformation resources, $\mathbb{R}_F = R_F \cup \mathscr{R}_F$.

Definition 2. Decision Resource: A resource $\mathbb{r}_D \in \mathbb{R}_D$ capable of advising the operand, an individual, on how to proceed next with the healthcare delivery system. They include *human* decision resources $r_D \in R_D$ (e.g. oncologist, general practitioner, surgeon) and *technical* decision resources $\mathscr{r}_D \in \mathscr{R}_D$ (e.g. decision support systems, electronic medical record decision tools). Decision resources are the set union of human and technical decision resources, $\mathbb{R}_D = R_D \cup \mathscr{R}_D$.

Definition 3. Measurement Resource: A resource $\mathbb{r}_M \in \mathbb{R}_M$ capable of measuring the operand: here the health state of an individual. They include *human* measurement resources $r_M \in R_M$ (e.g. MRI technician, sonographer, phlebotomist) and *technical* measurement resources $\mathscr{r}_M \in \mathscr{R}_M$ (e.g. magnetic resonance imaging scanner, ultrasound machine, holter monitor). Measurement resources are the set union of human and technical measurement resources, $\mathbb{R}_M = R_M \cup \mathscr{R}_M$.

Definition 4. Transportation Resource: A resource $\mathbb{r}_N \in \mathbb{R}_N$ capable of transporting its operand: the individual them self. They include *human* transportation resources $r_N \in R_N$ (e.g. runners, emergency medical technician, clinical care coordinator) and *technical* transportation resources $\mathscr{r}_N \in \mathscr{R}_N$ (e.g. ambulance, gurney, wheelchair). Transportation resources are the set union of human and technical transportation resources, $\mathbb{R}_N = R_N \cup \mathscr{R}_N$.

It is useful to define the set of non-transportation related resources.

Definition 5. Buffer Resource: A resource $r \in \mathbb{R}_B$, denoting specified locations as a set union of transformation, decision and measurement resources, where

$$\mathbb{R}_B = \mathbb{R}_F \cup \mathbb{R}_D \cup \mathbb{R}_M \quad (1)$$

The healthcare delivery system resources described thus far allows specific instances to be non-uniquely classified. In the cases where a specific resource is capable of performing several processes, it is must be uniquely classified. In order to create a unique classification of these resources, a set of ordered classification rules are implemented.

Definition 6. Rules for Classification of Healthcare System Resources:

Rule 1: If $r \in R$ can *Transform*; then $r \in R_F$. If $\mathscr{r} \in \mathscr{R}$ can *Transform*; then $\mathscr{r} \in \mathscr{R}_{\mathscr{F}}$.
Rule 2: If $r \in R$ can *Decide*; then $r \in R_D$. If $\mathscr{r} \in \mathscr{R}$ can *Decide*; then $\mathscr{r} \in \mathscr{R}_{\mathscr{D}}$.
Rule 3: If $r \in R$ can *Measure*; then $r \in R_M$. If $\mathscr{r} \in \mathscr{R}$ can *Measure*; then $\mathscr{r} \in \mathscr{R}_{\mathscr{M}}$.
Rule 4: Otherwise $r \in R_N$ and $\mathscr{r} \in \mathscr{R}_{\mathscr{N}}$

B. System Function

The healthcare delivery system is composed of processes $P = P_F \cup P_D \cup P_M \cup P_N$ representing the system Function. Four types of processes have been defined [16]:

Definition 7. Transformation Process: A *physical* process $p_F \in P_F$ that transforms the operand: specifically the internal health state of the individual (i.e. treatment of condition, disease or disorder).

Definition 8. Decision Process: A *cyber-physical* process $p_D \in P_D$ occurring between a healthcare system resource and the operand: the individual, that generates a decision on how to proceed next with the healthcare delivery system.

Definition 9. Measurement Process: A *cyber-physical* process $p_M \in P_M$ that converts a physical property of the operand into a cyber, informatic property to ascertain health state of the individual.

Definition 10. Transportation Process: A *physical* process $p_N \in P_N$ that moves individuals between healthcare resources (e.g. bring individual to emergency department, move individual from operating to recovery room).

The introduction of the set of buffer resources $\mathbb{R}_B$ (in Definition 5) implies that there are $\sigma^2(\mathbb{R}_B)$ transportation processes where the $\sigma()$ notation is introduced to give the size of a set. As a matter of convention, a healthcare process p_{Nu} transports an individual from resource $r_{y_1} \in \mathbb{R}_B$ to resource $r_{y_2} \in \mathbb{R}_B$ according to the index convention [17]–[23]: $u = \sigma(\mathbb{R}_B)(y_1 - 1) + y_2$.

Definition 11. Non-Transportation Process: A combination of non-transportation processes representing transformation, decision and measurement process, $p_B \in P_B$ that is a set union of non-transportation processes. $P_B = P_F \cup P_D \cup P_M$.

C. System Concept

The system concept is defined as an allocated architecture composed of a bipartite graph between system processes and resources, that can be mathematically described as [17]–[23]. $P = J_S \odot \mathbb{R}$, where J_S is the system knowledge base.

Definition 12. System Knowledge Base [17]–[23]: A binary matrix J_S of size $\sigma(P) \times \sigma(\mathbb{R})$ whose element $J_S(w, v) \in \{0, 1\}$ is equal to one when event $e_{wv} \in \mathcal{E}_S$ (in the discrete event systems sense [24]) exists as a system process $p_w \in P$ being executed by a resource $r_v \in \mathbb{R}$. It may be calculated directly as

$$J_S = \begin{bmatrix} J_F & 0 & 0 & 0 \\ J_{FD} & J_D & 0 & 0 \\ J_{FM} & J_{DM} & J_M & 0 \\ J_{FN} & J_{DN} & J_{MN} & J_N \end{bmatrix} \quad (2)$$

The healthcare delivery system knowledge base J_S represents the elemental capabilities that *exist* within the system. These capabilities may not always be *available* and therefore such constraints can be described in a similar structure called the system events constraints matrix.

Designing patient-oriented healthcare services as Systems of Systems for the integration of behavioral health into primary care is an example of care for a chronic condition. In the situation of chronic care, the duration of a chronic episode is much longer than a duration of a facility visit. For that reason transportation resources and processes are abstracted out as insignificant relative to the time-frame of the chronic condition.

III. Methodology

At a local hospital, a team was assembled and tasked with determining a model for integrating behavioral health into primary care for an initial implementation at a test site, to be further rolled out in the future as a system-wide model to several other sites. The team included a systems engineering researcher and personnel from the Departments of Psychiatry and Internal Medicine.

The team proceeded to develop the integrated behavioral health service as they typically would, with a heavy focus on the clinical aspect of the model followed by the operational aspect of the service model. During this time a system model of the service from an engineering perspective was developed.

First, the healthcare service model was described from a system Form and Function by identifying the resources and processes using the methodology presented in Section II and described in more detail in prior work [13]. Next, the system knowledge base was constructed, describing the resources performing each function at several clinically appropriate levels. This included a high-level description of the model as is typically presented in healthcare. Next, more specified levels describing the details of the operations were constructed. This was prepared so as to highlight specific pros of integration.

Next, the model-based systems engineering tool, SysML, was used to graphically represent the system of systems service.

Finally, the model was presented and validated through individual and group feedback.

IV. Results

A. Clinical Model Description

There are several clinical models describing varying levels of integration of behavioral health into primary care. One of the typically referenced models is the *Collaborative Care Model* based on the IMPACT trial [25]. It is typically visually presented using the Collaborative Care Team Structure, published initially in 2015, shown in Figure 1, [26] and updated in 2017 with a newer figure, shown in Figure 2, [27].

The *functional* model has several figures that describe different aspects of the model, such as the stepped care aspect of the model [28], a tasks check-list [29], or the step-by-step guide to implementing the model described as a one-page document of high level tasks [30]. The tasks as the closest description of functions or activities are shown in Figure 3.

B. System Model Description

Modeling healthcare functions and tasks was performed based on the published *Healthcare Functional Model Concept of healthcare system processes* [13]. These functions are based on a clinical *diagnostic model* [31] that first examines the patient's complaint or concern (measure), second, decides on the cause of the issue or how to proceed next (diagnose & decide) and third, applies a treatment regiment to that cause (treat or transform). A high level functional model is adapted here for Integrated Behavioral Health in Figure 4.

SysML figures representing the highest level of System Form and System Function are presented in Figures 5 and 6, respectively. The multi-level system model incorporates 3 levels of the model. An example third level (lowest level) description of providing ongoing measurement and followup of behavioral health levels is shown in Figure 7. It includes the closest part of the distinguishing "stepped care aspect" of the IMPACT trial, where if the patient is not improving, they are moved to a higher level of treatment in a stepped fashion.

V. Conclusion

In conclusion, this paper presents a description of integrating behavioral health into primary care using a systems engineering framework and model-based systems engineering tools to describe a typical clinical model as a system model. By doing so, it alleviates many of the clinical methods limitations by describing the system from a systems perspective detailing system form and function, detailing the descriptions in multiple levels and describing the model from a patient-perspective, thus allowing the model to be quantified.

Future work utilizes the described modeling methodology and framework to enumerate both the healthcare delivery system and individual patient trajectories. This is a key missing feature which is undoubtedly needed and typically requested by healthcare delivery systems as evaluations.

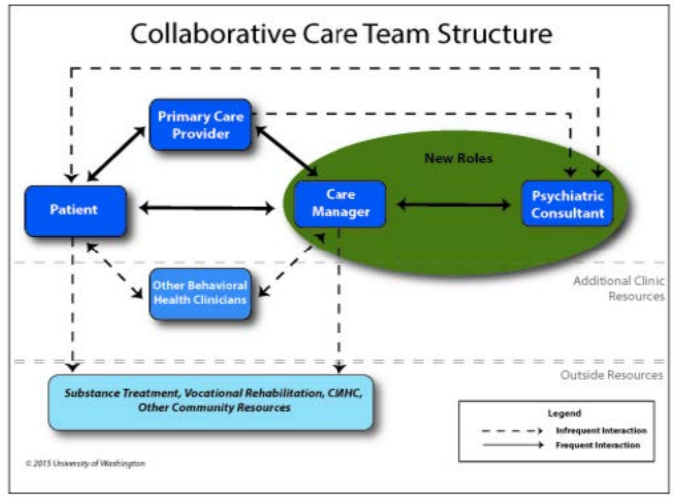

Fig. 1. Collaborative Care team structure figure published in 2015 [26].

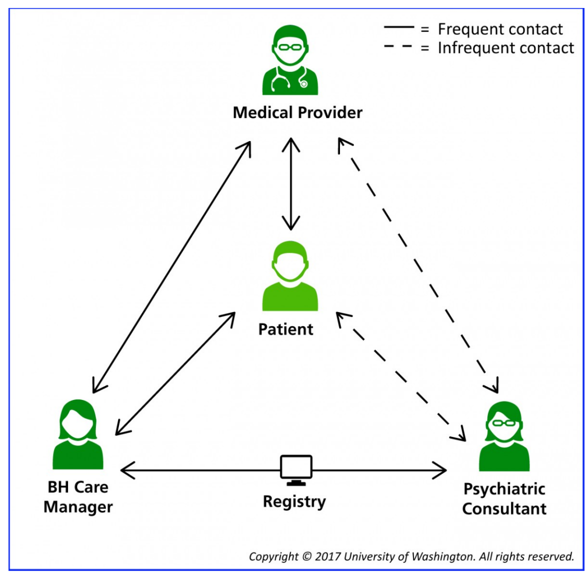

Fig. 2. Collaborative Care team structure figure published in 2017 [27].

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Core Components & Tasks

1. Patient Identification and Diagnosis
Screen for behavioral health problems using valid instruments
Diagnose behavioral health problems and related conditions
Use valid measurement tools to assess and document baseline symptom severity
2. Engagement in Integrated Care Program
Introduce collaborative care team and engage patient in integrated care program
Initiate patient tracking in population-based registry
3. Evidence-Based Treatment
Develop and regularly update a biopsychosocial treatment plan
Provide patient and family education about symptoms, treatments, and self management skills
Provide evidence-based counseling (e.g., Motivational Interviewing, Behavioral Activation)
Provide evidence-based psychotherapy (e.g., Problem Solving Treatment, Cognitive Behavior Therapy, Interpersonal Therapy)
Prescribe and manage psychotropic medications as clinically indicated
Change or adjust treatments if patients do not meet treatment targets
4. Systematic Follow-up, Treatment Adjustment, and Relapse Prevention
Use population-based registry to systematically follow all patients
Proactively reach out to patients who do not follow-up
Monitor treatment response at each contact with valid outcome measures
Monitor treatment side effects and complications
Identify patients who are not improving to target them for psychiatric consultation and treatment adjustment
Create and support relapse prevention plan when patients are substantially improved
5. Communication and Care Coordination
Coordinate and facilitate effective communication among providers
Engage and support family and significant others as clinically appropriate
Facilitate and track referrals to specialty care, social services, and community-based resources
6. Systematic Psychiatric Case Review and Consultation
Conduct regular (e.g., weekly) psychiatric caseload review on patients who are not improving
Provide specific recommendations for additional diagnostic work-up, treatment changes, or referrals
Provide psychiatric assessments for challenging patients in-person or via telemedicine
7. Program Oversight and Quality Improvement
Provide administrative support and supervision for program
Provide clinical support and supervision for program
Routinely examine provider- and program-level outcomes (e.g., clinical outcomes, quality of care, patient satisfaction) and use this information for quality improvement

Fig. 3. Collaborative Care tasks adapted from [29].

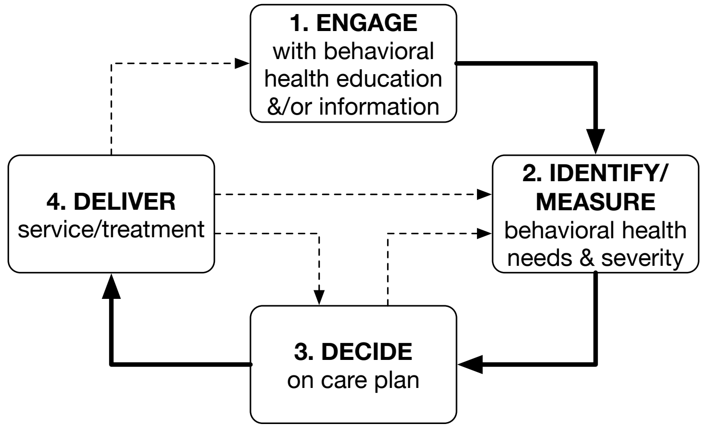

Fig. 4. High-level functional model for Integrated Behavioral Health.

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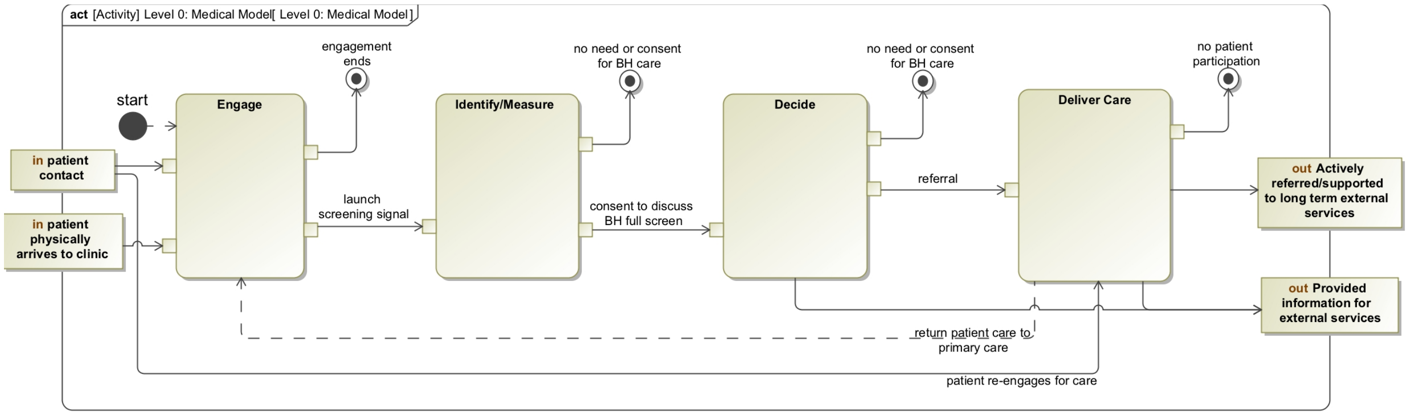

Fig. 5. Highest level, 1st level functional model for the Integrated Behavioral Health Service.

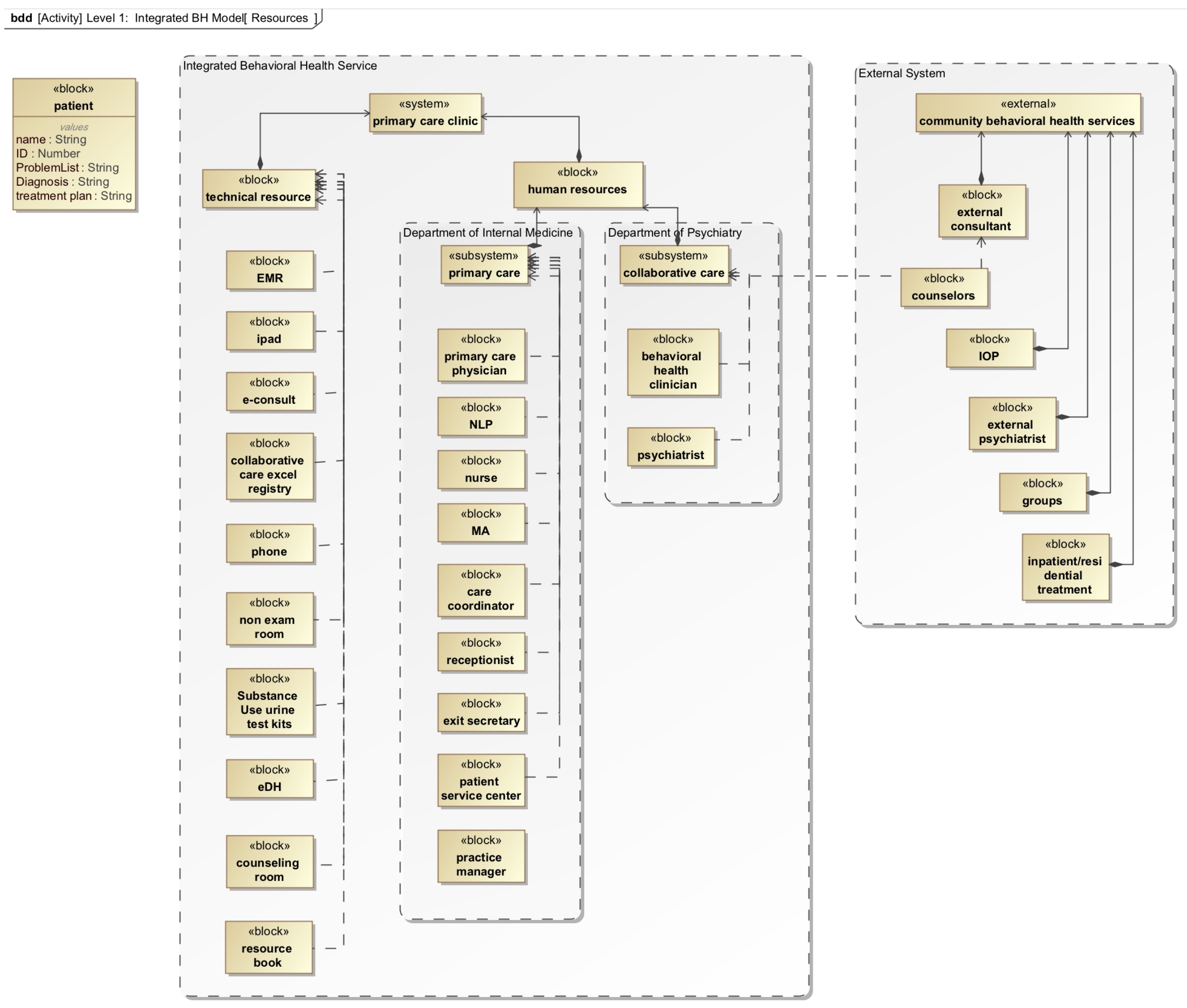

Fig. 6. Resources in the Integrated Behavioral Health Service.

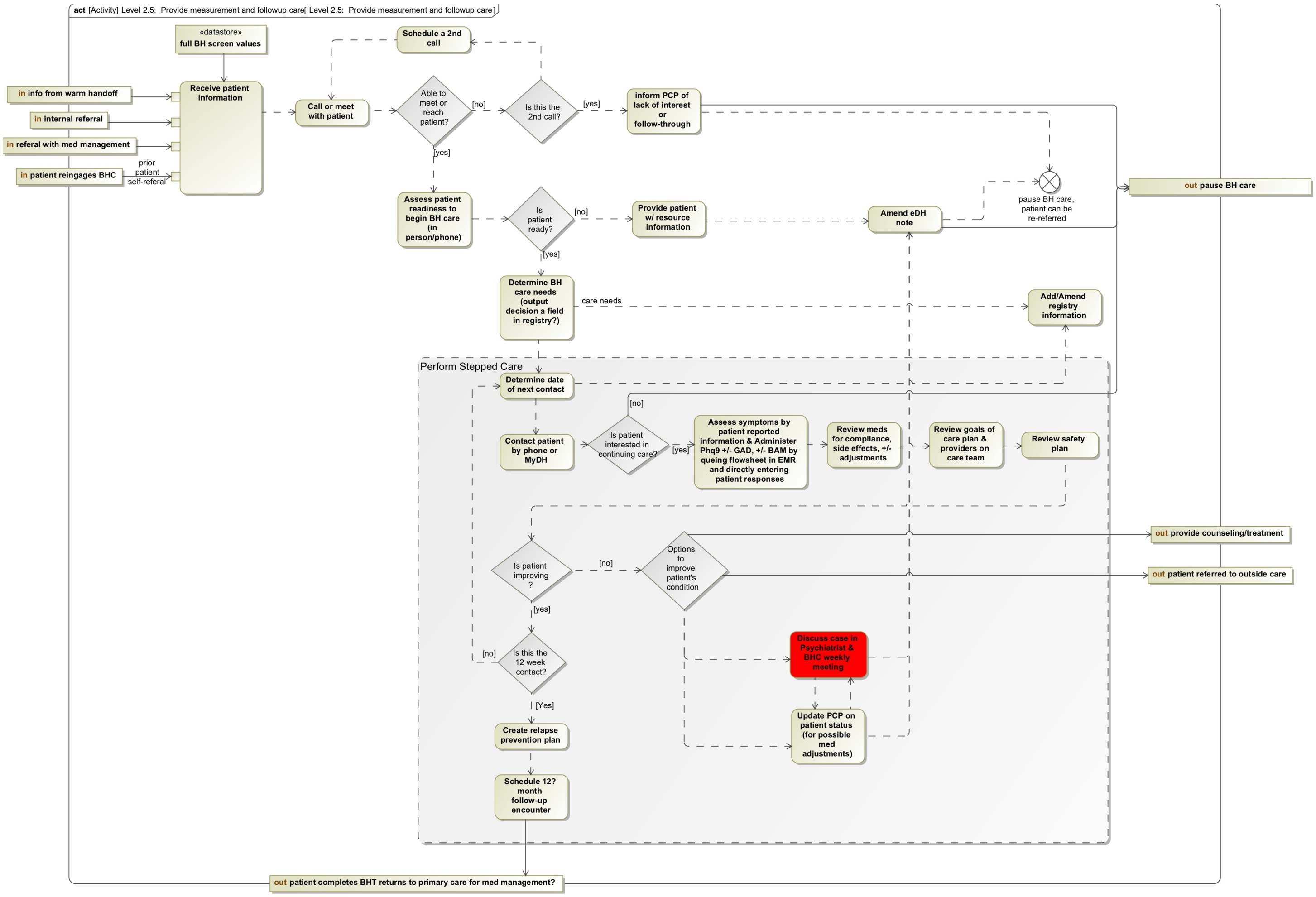

Fig. 7. 3rd level providing ongoing measurement and followup care.

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