ON $\theta$-GENERALIZED CLOSED SETS

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ABSTRACT. The aim of this paper is to study the class of $\theta$-generalized closed sets, which is properly placed between the classes of generalized closed and $\theta$-closed sets. Furthermore, generalized $\Lambda$-sets \[16\] are extended to $\theta$-generalized $\Lambda$-sets and $R_0$, $T_{1/2}$- and $T_1$-spaces are characterized. The relations with other notions directly or indirectly connected with generalized closed sets are investigated. The notion of TGO-connectedness is introduced.

Keywords and phrases. $\theta$-generalized closed, $\theta$-closure, $\Lambda$-set, TGO-connected.

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1. Introduction. The first step of generalizing closed sets was done by Levine in 1970 \[15\]. He defined a set $A$ to be generalized closed if its closure belongs to every open superset of $A$ and introduced the notion of $T_{1/2}$-spaces, which is properly placed between $T_0$-spaces and $T_1$-spaces. Dunham \[10\] proved that a topological space is $T_{1/2}$ if and only if every singleton is open or closed. In \[13\], Khalimsky, Kopperman, and Meyer proved that the digital line is a typical example of a $T_{1/2}$-space.

Ever since, general topologists extended the study of generalized closed sets on the basis of generalized open sets: regular open, $\alpha$-open \[20\], semi-open \[14\], semi-preopen \[1\], preopen \[19\], $\theta$-open \[26\], $\delta$-open \[26\], etc.

Extensive research on generalizing closedness was done in recent years as the notions of semi-generalized closed, generalized semi-closed, generalized $\alpha$-closed, $\alpha$-generalized closed, generalized semi-preclosed, regular generalized closed, $\gamma$-g-closed and $(\gamma, \gamma')$-g-closed sets were investigated \[2, 3, 6, 7, 11, 18, 17, 22, 23, 24, 25\].

Recently, in \[8\], Ganster and the first author of this paper defined $\delta$-generalized closed sets and introduced the notion of $T_{3/4}$-spaces, which is properly placed between $T_1$-spaces and $T_{1/2}$-spaces. They proved that the digital line is $T_{3/4}$.

The aim of this paper is to continue the study of generalized closed sets, this time via the $\theta$-closure operator defined in \[26\] and characterize $T_{1/2}$-spaces and $T_1$-spaces in terms of $\theta$-generalized closed sets. Via $\theta$-closure operator, we extend the class of generalized $\Lambda$-sets to the class of $\theta$-generalized $\Lambda$-sets and study some new characterizations of $R_0$-spaces and $T_1$-spaces.

2. Preliminaries concerning generalized closed sets. Throughout this paper, we consider spaces on which no separation axioms are assumed unless explicitly stated. The topology of a given space $X$ is denoted by $\tau$ and $(X, \tau)$ is replaced by $X$ if there is no chance for confusion. For $A \subseteq X$, the closure and the interior of $A$ in $X$ are denoted by $\mathrm{Cl}(A)$ and $\mathrm{Int}(A)$, respectively. Sometimes, when there is no chance for
confusion, $\bar{A}$ stands for $\text{Cl}(A)$. The $\theta$-interior [26] of a subset $A$ of $X$ is the union of all open sets of $X$ whose closures are contained in $A$, and is denoted by $\text{Int}_\theta(A)$. The subset $A$ is called $\theta$-open [26] if $A = \text{Int}_\theta(A)$. The complement of a $\theta$-open set is called $\theta$-closed. Alternatively, a set $A \subseteq (X, \tau)$ is called $\theta$-closed [26] if $A = \text{Cl}_\theta(A)$, where $\text{Cl}_\theta(A) = \{x \in X : U \cap A \neq \emptyset, U \in \tau \text{ and } x \in U\}$. The family of all $\theta$-open sets forms a topology on $X$ and is denoted by $\tau_\theta$. We use the name CO-set for sets whose closure is open.

**Observation 2.1.**

(i) If $A$ is preopen, then $\text{Cl}_\alpha(A) = \text{Cl}(A) = \text{Cl}_\theta(A)$.

(ii) Every CO-set is preopen.

(iii) Every dense subset is a CO-set.

(iv) Every subset of a space $(X, \tau)$ is a CO-set if and only if $(X, \tau)$ is locally indiscrete.

**Definition 1.** A subset $A$ of a space $(X, \tau)$ is called

1. a generalized closed set (= g-closed) [15] if $A \subseteq U$ and $U \in \tau$ implies that $\bar{A} \subseteq U$,
2. a semi-generalized closed set (= sg-closed) [4] if $A \subseteq U$ and $U$ is semi-open implies that $\bar{s\text{Cl}(A)} \subseteq U$,
3. a generalized $\alpha$-closed set (= $g\alpha$-closed) [17] if $A \subseteq U$ and $U$ is $\alpha$-open implies that $\bar{s\text{Cl}(A)} \subseteq U$,
4. a generalized semi-closed set (= gs-closed) [2] if $A \subseteq U$ and $U \in \tau$ implies that $\bar{s\text{Cl}(A)} \subseteq U$,
5. an $\alpha$-generalized closed set (= $\alpha$ g-closed) [18] if $A \subseteq U$ and $U \in \tau$ implies that $\bar{\text{Cl}_\alpha(A)} \subseteq U$,
6. a generalized semi-preclosed set (= gsp-closed) [7] if $A \subseteq U$ and $U \in \tau$ implies that $\bar{\text{spCl}(A)} \subseteq U$,
7. a regular generalized closed set (= r-g-closed) [23] if $A \subseteq U$ and $U$ is regular open implies that $\bar{A} \subseteq U$.

**Definition 2.** A topological space $(X, \tau)$ is called

1. $R_0$-space [5] if the closures of every two different points are either disjoint or coincide,
2. $R_1$-space [5] if every two different points, with distinct closures, have disjoint neighborhoods,
3. $T_{1/2}$-space [15] if every g-closed set is closed (= every singleton is open or closed [10]),
4. $kc$-space [27] if every compact set is closed.

**Definition 3.** Recall that a function $f : (X, \tau) \to (Y, \sigma)$ is called

1. $g$-continuous [3] if $f^{-1}(V)$ is g-closed in $(X, \tau)$ for every closed set $V$ of $(Y, \sigma)$,
2. semi-continuous [14] if $f^{-1}(V)$ is semi-open in $(X, \tau)$ for every open set $V$ of $(Y, \sigma)$,
3. strongly $\theta$-continuous [21] if, for each $x \in X$ and each open set $V$ containing $f(x)$, there exists an open set $U$ containing $x$ such that $f(U) \subseteq V$.

3. Basic properties of $\theta$-generalized closed sets

**Definition 4.** A subset $A$ of a topological space $(X, \tau)$ is called $\theta$-generalized closed (= $\theta$-g-closed) if $\text{Cl}_\theta(A) \subseteq U$, whenever $A \subseteq U$ and $U$ is open in $(X, \tau)$.
We denote the family of all $\theta$-generalized closed subsets of a space $(X, \tau)$ by $\text{TGC}(X, \tau)$.

The next two results together with the examples following them show that the class of $\theta$-generalized closed sets is properly placed between the classes of $g$-closed and $\theta$-closed sets.

**Observation 3.1.** Every $\theta$-closed set is $\theta$-generalized closed.

**Example 3.2.** Let $X = \{a, b, c\}$ and let $\tau = \{\emptyset, \{a, b\}, X\}$. Set $A = \{a, c\}$. Since the only open superset of $A$ is $X$, $A$ is clearly $\theta$-generalized closed. But it is easy to see that $A$ is not $\theta$-closed. In fact, it is not even semi-closed since its complement $\{b\}$ has empty interior.

**Observation 3.3.** Every $\theta$-generalized closed set is $g$-closed and hence $\alpha g$-closed, $gs$-closed, and $r g$-closed.

**Example 3.4.** Let $X = \{a, b, c\}$ and let $\tau = \{\emptyset, \{a\}, \{a, b\}, \{a, c\}, X\}$. Set $A = \{c\}$. Clearly, $A$ is closed and hence $g$-closed. Next, set $U = \{a, c\}$. Note that $X = \text{Cl}_\theta(A) \notin U \in \tau$. Thus, $A$ is not $\theta$-generalized closed.

The following diagram is an enlargement of a Diagram from [7].

**Observation 3.5.** Let $(X, \tau)$ be a regular space (not necessarily even $T_0$). Then a subset $A$ of $X$ is $\theta$-generalized closed if and only if $A$ is generalized closed.

**Lemma 3.6** [12, Thm. 3.1(d), Thm. 3.6(d)]. For a space $(X, \tau)$, the following conditions are equivalent

1. $X$ is an $R_1$-space;
2. for each $x \in X$, $\text{Cl}_\theta(x) = \text{Cl}_\theta\{x\}$;
3. for each compact set $A \subseteq X$, $\text{Cl}(A) = \text{Cl}_\theta(A)$.

**Proposition 3.7.** If $(X, \tau)$ is $R_1$, then a compact subset $K$ of $X$ is $g$-closed if and only if $K$ is $\theta$-g-closed.

**Proposition 3.8.** Let $A$ be a preopen subset of a topological space $(X, \tau)$. Then the
following conditions are equivalent
(1) $A$ is $\theta$-g-closed;
(2) $A$ is $g$-closed;
(3) $A$ is $\alpha g$-closed.

**Proof.** Follows easily from Observation 2.1(i) (note that a preopen g-closed set is a CO-set).

**Lemma 3.9.** If $A$ and $B$ are subsets of a topological space $(X, \tau)$, then $\text{Cl}_\theta(A \cup B) = \text{Cl}_\theta(A) \cup \text{Cl}_\theta(B)$ and $\text{Cl}_\theta(A \cap B) \subseteq \text{Cl}_\theta(A) \cap \text{Cl}_\theta(B)$.

**Proposition 3.10.** (i) A finite union of $\theta$-g-closed sets is always a $\theta$-g-closed set.
(ii) A countable union of $\theta$-g-closed sets need not be a $\theta$-g-closed set.
(iii) A finite intersection of $\theta$-g-closed sets may fail to be a $\theta$-g-closed set.

**Proof.** (i) Let $A, B \in \text{TGC}(X)$. Let $U \in \tau$ such that $A \cup B \subseteq U$. By Lemma 3.9, $\text{Cl}_\theta(A \cup B) = \text{Cl}_\theta(A) \cup \text{Cl}_\theta(B) \subseteq U \cup U = U$ since $A$ and $B$ are $\theta$-g-closed. Hence, $A \cup B$ is $\theta$-g-closed.

(ii) Let $X$ be the real line with the usual topology. Since $X$ is regular, by Observation 3.5, every singleton in $X$ is $\theta$-g-closed. Set $A = \bigcup_{i=2}^{\infty} \{1/i\}$. Clearly, $A$ is a countable union of $\theta$-generalized closed sets but $A$ is not $\theta$-generalized closed since $A \subseteq (0,1)$ and $0 \in \text{Cl}_\theta(A)$.

(iii) Let $X = \{a, b, c, d, e\}$ and let $\tau = \{\emptyset, \{a, b\}, \{c\}, \{a, b, c\}, X\}$. Set $A = \{a, c, d\}$ and $B = \{b, c, e\}$. Clearly, $A$ and $B$ are $\theta$-generalized closed sets since $X$ is their only open superset. But $C = \{c\} = A \cap B$ is not $\theta$-generalized closed since $C \subseteq \{c\} \in \tau$ and $\text{Cl}_\theta(C) = \{c, d, e\} \notin \{c\}$.

**Proposition 3.11.** The intersection of a $\theta$-generalized closed set and a $\theta$-closed set is always $\theta$-generalized closed.

**Proof.** Let $A$ be $\theta$-generalized closed and let $F$ be $\theta$-closed. Let $U$ be an open set such that $A \cap F \subseteq U$. Set $G = X \setminus F$. Then $A \subseteq U \cup G$. Since $G$ is $\theta$-open, $U \cup G$ is open and since $A$ is $\theta$-generalized closed, $\text{Cl}_\theta(A) \subseteq U \cup G$. Now, by Lemma 3.9, $\text{Cl}_\theta(A \cap F) \subseteq \text{Cl}_\theta(A) \cap \text{Cl}_\theta(F) = \text{Cl}_\theta(A) \cap F \subseteq (U \cup G) \cap F = (U \cap F) \cup (G \cap F) = (U \cap F) \cup \emptyset \subseteq U$.

**Proposition 3.12.** Let $B \subseteq H \subseteq (X, \tau)$ and $(\text{Cl}_\theta)_H(B)$ denote the $\theta$-closure of $B$ in the subspace $(H, \tau \mid H)$. Then
(i) $(\text{Cl}_\theta)_H(B) \subseteq \text{Cl}_\theta(B) \cap H$ holds.
(ii) If $H$ is open in $(X, \tau)$, then $(\text{Cl}_\theta)_H(B) \supseteq \text{Cl}_\theta(B) \cap H$ holds.

**Theorem 3.13.** Let $B \subseteq H \subseteq (X, \tau)$.
(i) If $B$ is $\theta$-g-closed relative to $H$ (i.e., $B \in \text{TGC}(H, \tau \mid H)$), $H \in \text{TGC}(X)$, and $H \in \tau$, then $B \in \text{TGC}(X)$.

(ii) If $B$ is $\theta$-g-closed in $(X, \tau)$, then $B$ is $\theta$-g-closed relative to $H$ (i.e., $B \in \text{TGC}(H, \tau \mid H)$).

**Proof.** (i) Let $B \subseteq U$, where $U \in \tau$. Then $B \subseteq H \cap U$ and, moreover, $(\text{Cl}_\theta)_H(B) \subseteq H \cap U$ due to assumption. By Proposition 3.12(ii), $H \cap \text{Cl}_\theta(B) \subseteq H \cap U \subseteq U$. Using the last inclusion, it follows that $H \subseteq H \cup (X \setminus \text{Cl}_\theta(B)) = (H \cap \text{Cl}_\theta(B)) \cup (X \setminus \text{Cl}_\theta(B)) \subseteq U \cup (X \setminus \text{Cl}_\theta(B))$. Since $\text{Cl}_\theta(B)$ is a closed set, $U \cup (X \setminus \text{Cl}_\theta(B))$ is open and thus since $H \in \text{TGC}(X)$, $\text{Cl}_\theta(H) \subseteq U \cup (X \setminus \text{Cl}_\theta(B))$. Now, $\text{Cl}_\theta(B) \subseteq \text{Cl}_\theta(H) \subseteq U \cup (X \setminus \text{Cl}_\theta(B))$. From the
last inclusion, it follows that $\text{Cl}_\theta(B) \subseteq U$ or, equivalently, $B \in \text{TGC}(X)$.

(ii) Let $V$ be an open set of $(H, \tau \mid H)$ such that $B \subseteq V$. Then there exists an open set $G \in \tau$ such that $G \cap H = V$. Since $B \subseteq G \cap H \subseteq G$ and $B \in \text{TGC}(X)$, $\text{Cl}_\theta(B) \subseteq G$. By Proposition 3.12(i), $(\text{Cl}_\theta)_B(H) \subseteq \text{Cl}_\theta(B) \cap H \subseteq G \cap H \subseteq V$. Therefore, $B$ is $\theta$-g-closed relative to $H$.

\begin{example}
Let $X = \{a, b, c, d\}$ and $\tau = \{\emptyset, \{a\}, \{a, b\}, \{a, c, d\}, X\}$. Then $\{\emptyset, X\}$ is the set of all $\theta$-closed sets of $(X, \tau)$ and $\text{TGC}(X, \tau) = \{\emptyset, \{b, c\}, \{b, d\}, \{b, c, d\}, \{a, b, c\}, X\}$. Let $H = \{b, c, d\}$ be a set of $X$. Then, $\tau \mid H = \{\emptyset, \{b\}, \{c, d\}, H\}$. Note that $\{\emptyset, \{b\}, \{c, d\}, H\}$ is the set of all $\theta$-closed sets of $(H, \tau \mid H)$ and $\text{TGC}(H, \tau \mid H) = \emptyset$. The subset $\{b\}$ of $H$ is $\theta$-g-closed relative to $H$ and $H$ is not open (i.e., $\{b\} \in \text{TGC}(H, \tau \mid H)$, $H \notin \tau$) and $H \in \text{TGC}(X, \tau)$. However, $\{b\} \notin \text{TGC}(X, \tau)$.

\end{example}

\begin{example}
Let $(X, \tau)$ be the space in the example above. Set $H = \{a, c, d\}$. Clearly, $H$ is open in $(X, \tau)$ and $H$ is not $\theta$-generalized closed in $(X, \tau)$. But $B = \{a, c\}$ is $\theta$-generalized closed relative to $H$. However, $B$ is not $\theta$-generalized closed in $(X, \tau)$.

\end{example}

\section{Characterizations of $T_{1/2}$-spaces, $T_1$-spaces and $R_0$-spaces}

\begin{theorem}
A space $(X, \tau)$ is a $T_{1/2}$-space if and only if every $\theta$-generalized closed set is closed.

\end{theorem}

\begin{proof}
\textbf{Necessity.} Let $A \subseteq X$ be $\theta$-generalized closed. By Observation 3.3, $A$ is g-closed. Since $X$ is a $T_{1/2}$-space, $A$ is closed.

\textbf{Sufficiency.} Let $x \in X$. If $\{x\}$ is not closed, then $B = X \setminus \{x\}$ is not open and thus the only superset of $B$ is $X$. Trivially, $B$ is $\theta$-generalized closed. By (2), $B$ is closed or, equivalently, $\{x\}$ is open. Thus, every singleton in $X$ is open or closed. Hence, in the notion of [6, Thm. 6.2(i)], $X$ is a $T_{1/2}$-space.

\end{proof}

\begin{lemma}
Let $A \subseteq (X, \tau)$ be $\theta$-generalized closed. Then $\text{Cl}_\theta(A) \setminus A$ does not contain a nonempty closed set.

\end{lemma}

\begin{proof}
\textbf{Necessity.} Let $A \subseteq X$ be $\theta$-generalized closed and let $x \in \text{Cl}_\theta(A)$. Since $X$ is $T_1$, $\{x\}$ is closed and thus by Lemma 4.2, $x \notin \text{Cl}_\theta(A) \setminus A$. Since $x \in \text{Cl}_\theta(A)$, then $x \in A$. This shows that $\text{Cl}_\theta(A) \subseteq A$ or, equivalently, that $A$ is $\theta$-closed.

\textbf{Sufficiency.} Let $x \in X$. Assume that $\{x\}$ is not closed. Then $B = X \setminus \{x\}$ is not open and, trivially, $B$ is $\theta$-generalized closed since the only open superset of $B$ is $X$ itself. By (2), $B$ is $\theta$-closed and thus $\{x\}$ is $\theta$-open. Since a singleton is $\theta$-open if and only if it is clopen, $\{x\}$ is clopen.

\end{proof}

The notion of a $\Lambda$-set and a generalized $\Lambda$-set in a topological space was introduced in [16]. By definition, a subset $A$ of a topological space $(X, \tau)$ is called a $\Lambda$-set [16] if $A = A^\Lambda$, where $A^\Lambda = \cap \{U : U \supset A, U \in \tau\}$. Recall that $A$ is called a generalized $\Lambda$-set [16] if $A^\Lambda \subseteq F$, whenever $A \subseteq F$ and $F$ is $\tau$-closed.
Definition 5. (i) For a subset $A$ of $(X, \tau)$, we define $A^\Lambda_\theta$ as follows
\[ A^\Lambda_\theta = \{ x \in X : \text{Cl}_\theta \{ x \} \cap A \neq \emptyset \} . \]
In [12], $A^\Lambda_\theta$ is denoted by ker$_\theta A$.
(ii) A subset $A$ of $(X, \tau)$ is called $\theta$-generalized $\Lambda$-set ($= \theta$-$g$-$\Lambda$-set) if $A^\Lambda_\theta \subseteq F$, whenever $A \subseteq F$ and $F$ is closed in $(X, \tau)$.

Observation 4.4. (i) Every $G_\delta$-set is a $\Lambda$-set.
(ii) [12, Lem. 3.5(a)]. For any set $A \subseteq X$, $A \subseteq A^\Lambda_\theta \subseteq \text{Cl}_\theta(A)$.
(iii) Every $\theta$-closed set is a $\Lambda$-set.
(iv) Every $g$-closed $\Lambda$-set is closed.
(v) Every $\theta$-generalized $\Lambda$-set is a generalized $\Lambda$-set.

Remark 4.5. (i) A $\Lambda$-set need not be $\theta$-closed. Any singleton of an infinite space with the cofinite topology is a $\Lambda$-set (since the space is $T_1$) but none of the singletons is $\theta$-closed.
(ii) A closed set need not be a $\Lambda$-set. In the Sierpinski space $(X = \{a, b\}, \tau = \{\emptyset, \{a\}, X\})$, the set $B = \{b\}$ is closed but $B$ is not a $\Lambda$-set. However, in [16, Prop. 3.8], it was shown that in a topological space $(X, \tau)$, every subset of $X$ is a generalized $\Lambda$-set if and only if every closed set is a $\Lambda$-set.
(iii) A generalized $\Lambda$-set need not be $\theta$-generalized $\Lambda$-set. In an infinite cofinite space $X$, as mentioned in Remark 4.5, every singleton is a $\Lambda$-set and, hence, a generalized $\Lambda$-set but none of the singletons is a $\theta$-generalized $\Lambda$-set since the $\theta$-closure of every singleton is $X$.

In [16], it was proved that in $T_1$-spaces, every set is a $\Lambda$-set. Note that the converse is also true.

Proposition 4.6. (i) A topological space $(X, \tau)$ is a $T_1$-space if and only if every subset of $X$ is a $\Lambda$-set.
(ii) A topological space $(X, \tau)$ is an $R_0$-space if and only if every singleton of $X$ is a generalized $\Lambda$-set.

Proof. (i) Obvious.
(ii) In [9], Dube showed that a space is $R_0$ if and only if, for each closed set $A$, $A = A^\Lambda$. Thus, if $X$ is $R_0$, then for each singleton $\{x\}$ and each closed set $F$ containing $x$, we have $\{x\} \subseteq \{x\}^\Lambda \subseteq F^\Lambda = F$. So, $\{x\}$ is a generalized $\Lambda$-set. For the reverse assume that $F \subseteq X$ is closed. For each $x \in F$, by assumption, $\{x\}^\Lambda \subseteq F$. Thus, $F^\Lambda = \bigcup_{x \in F} \{x\}^\Lambda \subseteq F$ according to [16, condition (2.5)]. This shows that $F = F^\Lambda$.

Observation 4.7. (i) A subset $A$ of an $R_1$-space $X$ is generalized $\Lambda$-set if and only if $A$ is $\theta$-generalized $\Lambda$-set.
(ii) In Hausdorff spaces, every subset is a $\theta$-generalized $\Lambda$-set.
(iii) A topological space $X$ is Hausdorff if and only if $X$ is a $kc$-space and every closed set of $X$ is a $\theta$-generalized $\Lambda$-set.

5. $\theta$-$g$-continuous and $\theta$-$g$-irresolute functions

Definition 6. A function $f : (X, \tau) \rightarrow (Y, \sigma)$ is called...
(1) \( \theta \)-g-continuous if \( f^{-1}(V) \) is \( \theta \)-g-closed in \( (X, \tau) \) for every closed set \( V \) of \( (Y, \sigma) \),

(2) \( \theta \)-g-irresolute if \( f^{-1}(V) \) is \( \theta \)-g-closed in \( (X, \tau) \) for every \( \theta \)-g-closed set \( V \) of \( (Y, \sigma) \).

**Observation 5.1.** If \( f : (X, \tau) \to (Y, \sigma) \) is strongly \( \theta \)-continuous, then \( f \) is \( \theta \)-g-continuous.

**Example 5.2.** Let \( (X, \tau) \) be the space in Example 3.2. Let \( \sigma = \{ \emptyset, \{b\}, X \} \). Let \( f : (X, \tau) \to (X, \sigma) \) be the identity function. Clearly, in the notion of Example 3.2, \( f \) is \( \theta \)-g-closed but \( f \) is not strongly \( \theta \)-continuous, not even semi-continuous.

**Observation 5.3.** Let \( f : (X, \tau) \to (Y, \sigma) \) be \( \theta \)-g-continuous. Then \( f \) is \( g \)-continuous but not conversely.

**Example 5.4.** Let \( (X, \tau) \) be the space in Example 3.4. Let \( \sigma = \{ \emptyset, \{a,b\}, X \} \). Let \( f : (X, \tau) \to (X, \sigma) \) be the identity function. Clearly, \( f \) is continuous and hence \( g \)-continuous but as shown in Example 3.4, \( A = \{c\} \notin TGC(X, \tau) \) and hence \( f \) is not \( \theta \)-g-continuous.

Example 5.2 and Example 5.4 also show that continuity and \( \theta \)-g-continuity are independent concepts. Thus, we have the following implications and none of them is reversible.

\[
\begin{array}{c}
\theta \text{-g-continuous} \\
\downarrow \\
\text{Strongly } \theta \text{-continuous} \\
\downarrow \\
\text{g-continuous} \\
\downarrow \\
\text{continuous}
\end{array}
\]

**Example 5.5.** Let \( f \) be the function in Example 5.2. Let \( \nu = \{ \emptyset, \{c\}, X \} \). Let \( g : (X, \sigma) \to (X, \nu) \) be the identity function. It is easily observed that \( g \) is also \( \theta \)-generalized continuous. But the composition function \( g \circ f : (X, \tau) \to (X, \nu) \) is not \( \theta \)-g-continuous since \( \{a,b\} \notin TGC(X, \tau) \).

**Theorem 5.6.** If \( f : (X, \tau) \to (Y, \sigma) \) is bijective, open and \( \theta \)-generalized continuous, then \( f \) is \( \theta \)-g-irresolute.

**Proof.** Let \( V \in TGC(Y) \) and let \( f^{-1}(V) \subseteq O \), where \( O \in \tau \). Clearly, \( V \subseteq f(O) \). Since \( f(O) \in \sigma \) and since \( V \in TGC(Y) \), \( Cl_\theta(V) \subseteq f(O) \) and thus \( f^{-1}(Cl_\theta(V)) \subseteq O \). Since \( f \) is \( \theta \)-generalized continuous and since \( Cl_\theta(V) \) is closed in \( Y \), \( Cl_\theta(f^{-1}(Cl_\theta(V))) \subseteq O \) and hence \( Cl_\theta(f^{-1}(V)) \subseteq O \). Therefore, \( f^{-1}(V) \in TGC(X) \). Hence, \( f \) is \( \theta \)-g-irresolute.

**Definition 7.** A function \( f : (X, \tau) \to (Y, \sigma) \) is called \( \theta \)-generalized closed if, for every closed set \( F \) of \( (X, \tau) \), \( f(F) \) is \( \theta \)-g-closed in \( (Y, \sigma) \).

**Theorem 5.7.** (i) Let \( f : (X, \tau) \to (Y, \sigma) \) be continuous and \( \theta \)-generalized closed. Then, for a \( \theta \)-g-closed set \( A \) of \( X \), \( f(A) \) is \( \theta \)-g-closed in \( Y \).
(ii) Let $f : (X, \tau) \to (Y, \sigma)$ be strongly $\theta$-continuous and closed. Then, $f$ is $\theta$-g-irresolute.

**Proof.** (i) Left to the reader.

(ii) Let $B$ be a $\theta$-g-closed set of $(Y, \sigma)$ and let $U \subseteq \tau$ such that $f^{-1}(B) \subseteq U$. Put $H = \text{Cl}_\theta(f^{-1}(B)) \cap (X \setminus U)$. A map $f : (X, \tau) \to (Y, \sigma)$ is strongly $\theta$-continuous if and only if $f : (X, \tau) \to (Y, \sigma)$ is $(\gamma, \text{id})$-continuous in the sense of Ogata [22, Def. 4.12], where $\gamma : \tau \to \mathcal{P}(X)$ is the closure operation and $\text{id} : \sigma \to \mathcal{P}(Y)$ is the identity operation. Using [22, Prop. 4.13(ii)] and the fact that $\text{Cl}_\gamma(E) = \text{Cl}_\theta(E)$ and $\text{Cl}_\text{id}(E) = \text{Cl}(E)$ for the closure operation $\gamma$, the identity operation $\text{id}$ and the subset $E$, we get $f(H) \subseteq f(\text{Cl}_\theta(f^{-1}(B))) \cap f(X \setminus B) \subseteq \text{Cl}(f(f^{-1}(B))) \cap (X \setminus B) \subseteq \text{Cl}(B) \setminus B \subseteq \text{Cl}(B) \setminus B$. By Lemma 4.2, $f(H) = \emptyset$ since $f(H)$ is closed. We have $H = \emptyset$ and hence $\text{Cl}_\theta(f^{-1}(B)) \subseteq U$. Therefore, $f^{-1}(B) \subseteq \text{TGC}(X, \tau)$.

**Corollary 5.8.** (i) Under the same assumptions of Theorem 5.6, if $(X, \tau)$ is $T_{1/2}$, then $(Y, \sigma)$ is $T_{1/2}$.

(ii) Under the same assumptions of Theorem 5.7(ii), if $(X, \tau)$ is $T_{1/2}$ and $f : (X, \tau) \to (Y, \sigma)$ is surjective, then $(Y, \sigma)$ is $T_{1/2}$.

**Proposition 5.9.** Let $f : (X, \tau) \to (Y, \sigma)$ be a $\theta$-generalized continuous function and let $H$ be a $\theta$-closed subset of $X$. Then the restriction $f \upharpoonright H : (H, \tau \upharpoonright H) \to (Y, \sigma)$ is $\theta$-generalized continuous.

**Proof.** Let $F$ be a closed subset of $(Y, \sigma)$. By Proposition 3.11, $H_1 = f^{-1}(F) \cap H$ is $\theta$-generalized closed in $(X, \tau)$. Then, by Theorem 3.13(iii), $H_1$ is $\theta$-g-closed in $(H, \tau \upharpoonright H)$. Since $(f \upharpoonright H)^{-1}(F) = H_1$, $f \upharpoonright H$ is $\theta$-g-continuous.

Next, we offer the following “Pasting Lemma” for $\theta$-g-continuous functions.

**Proposition 5.10.** Let $(X, \tau)$ be a topological space such that $X = A \cup B$, where both $A, B \subseteq \text{TGC}(X)$ and $A, B \subseteq \tau$. Let $f : (A, \tau \upharpoonright A) \to (Y, \sigma)$ and $g : (B, \tau \upharpoonright B) \to (Y, \sigma)$ be $\theta$-generalized continuous functions such that $f(x) = g(x)$ for every $x \in A \cap B$. Then the combination $\alpha : (X, \tau) \to (Y, \sigma)$ is $\theta$-generalized continuous, where $\alpha(x) = f(x)$ for any $x \in A$ and $\alpha(y) = g(y)$ for any $y \in B$.

**Definition 8.** A subset $A$ of $(X, \tau)$ is called $\theta$-generalized open (= $\theta$-g-open) if its complement $X \setminus A$ is $\theta$-generalized closed in $(X, \tau)$.

**Theorem 5.11.** (i) A subset $A$ of $(X, \tau)$ is $\theta$-g-open if and only if $F \subseteq \text{Int}_\theta(A)$, whenever $F \subseteq A$ and $F$ is closed in $(X, \tau)$.

(ii) If $A$ is $\theta$-g-open in $(X, \tau)$ and $B$ is $\theta$-g-open in $(Y, \sigma)$, then $A \times B$ is $\theta$-g-open in the product space $(X \times Y, \tau \times \sigma)$.

**Proof.** (i) Obvious.

(ii) Let $F$ be a closed subset of $(X \times Y, \tau \times \sigma)$ such that $F \subseteq A \times B$. For each $(x, y) \in F$, $\text{Cl}(\{x\}) \times \text{Cl}(\{y\}) \subseteq \text{Cl}(F) = F \subseteq A \times B$. Then the two closed sets $\text{Cl}(\{x\})$ and $\text{Cl}(\{y\})$ are contained in $A$ and $B$, respectively. By assumption, $\text{Cl}(\{x\}) \subseteq \text{Int}_\theta(A)$ and $\text{Cl}(\{y\}) \subseteq \text{Int}_\theta(B)$ hold. This implies that, for each $(x, y) \in F$, $(x, y) \in \text{Int}_\theta(A) \times \text{Int}_\theta(B) \subseteq \text{Int}_\theta(A \times B)$ and hence $F \subseteq \text{Int}_\theta(A \times B)$. By (i) it is clear that $A \times B$ is $\theta$-g-open.
**Proposition 5.12.** The projection \( p : (X \times Y, \tau \times \sigma) \rightarrow (X, \tau) \) is a \( \theta \)-g-irresolute map.

**Proof.** By definition and Theorem 5.11(ii), for a \( \theta \)-generalized closed set \( F \) of \((X, \tau)\), \( p^{-1}(x \setminus F) = (X \setminus F) \times Y \) is \( \theta \)-g-open in \((X \times Y, \tau \times \sigma)\). Therefore, \( P^{-1}(F) = F \times Y \) is \( \theta \)-generalized closed.


**Definition 9.** (cf. [15]). A topological space \( X \) is called TGO-connected (respectively, GO-connected [15]) if \( X \) cannot be written as a disjoint union of two nonempty \( \theta \)-g-open (respectively, \( g \)-open) sets. A subset of \( X \) is called TGO-connected if it is connected as a subspace.

Clearly, every TGO-connected space is connected. The space in [3, Ex. 11] shows that there are connected spaces which are not TGO-connected. Since every \( \theta \)-generalized closed set is \( g \)-closed, every GO-connected space is TGO-connected. Thus, we have the following implications and none of them is reversible.

\[ \text{GO-connected} \Rightarrow \text{TGO-connected} \Rightarrow \text{Connected} \]

**Example 6.1.** Let \( X = \{a, b, c, d\} \) and let \( \tau = \{\emptyset, \{a\}, \{a, b\}, \{a, c, d\}, X\} \). Since \( \{c\} \) is both \( g \)-closed and \( g \)-open, \( X \) is not GO-connected. Note that TGC\( (X) = \{\emptyset, \{b, c\}, \{b, d\}, \{a, b, c\}, \{a, b, d\}, \{b, c, d\}, X\} \). Hence, \( X \) is TGO-connected.

**Observation 6.2.** (i) [3, Prop. 10]. For a topological space \((X, \tau)\), the following conditions are equivalent.

1. \( X \) is TGO-connected;
2. the only subsets of \( X \), which are both \( \theta \)-g-open and \( \theta \)-g-closed, are \( \emptyset \) and \( X \);
3. each \( \theta \)-generalized continuous function of \( X \) into a discrete space \( Y \), with at least two points, is constant.

(ii) [3, Prop. 12]. If \((X, \tau)\) is a \( T_{1/2} \)-space, then the following conditions are equivalent

1. \( X \) is GO-connected;
2. \( X \) is TGO-connected;
3. \( X \) is connected.

(iii) A regular space \( X \) is GO-connected if and only if \( X \) is TGO-connected.

(iv) Let \( f : (X, \tau) \rightarrow (Y, \sigma) \) be a surjection. Then

(a) If \( f \) is \( \theta \)-generalized continuous and \( X \) is TGO-connected, then \( Y \) is connected.
(b) If \( f \) is \( \theta \)-g-irresolute and \( X \) is TGO-connected, then \( Y \) is TGO-connected.

**Corollary 6.3.** If the product space \((X \times Y, \tau \times \sigma)\) is TGO-connected, then its factor space \((X, \tau)\) is TGO-connected.

**Theorem 6.4.** Let \( f : (X, \tau) \rightarrow (Y, \sigma) \) be \( \theta \)-g-continuous. Then the image of every \( \theta \)-closed, TGO-connected subset of \((X, \tau)\) is connected in \((Y, \sigma)\).
Proof. Let $H$ be a $\theta$-closed and TGO-connected set in $(X, \tau)$. Then, by Proposition 5.9, the restriction of $f$ to $H$, $f | H : (H, \tau | H) \rightarrow (Y, \sigma)$, is $\theta$-g-continuous. For $f$, a function $r_H(f) : (H, \tau | H) \rightarrow (f(H), \sigma | f(H))$ is well defined by $(r_H(f))(x) = f(x)$ for any $x \in H$. Since $f | H = j \circ r_H(f)$, where $j : (f(H), \tau | f(H)) \rightarrow (Y, \sigma)$ is an inclusion. Then it is clear that $r_H(f)$ is $\theta$-g-continuous. In fact, for an open set $V$ of $(f(H), \sigma | f(H))$, take an open set $G \in \tau$ such that $G \cap f(H) = V$. Then $r_H(f)^{-1}(V) = (f \upharpoonright H)^{-1}(G)$ is $\theta$-g-open. Now, by Observation 6.2(iv), $(f(H), \sigma | f(H))$ is connected and hence $f(H)$ is a connected subset of $(Y, \sigma)$.

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